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# Homodyne detection readout for bit-oriented holographic memories

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Homodyne detection is proposed to increase the readout signal of bit-oriented holographic memories. It can be easily implemented on present memory architectures by making the diffracted signal interfere with a reflection of the reading beam. The large resulting increase of the readout signal can be used to enhance the data transfer rate. A first experimental demonstration of such a readout procedure is presented. © 2006 Optical Society of America

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Holographic data storage is a promising technique to develop optical disks with up to terabyte capacities. Whereas conventional approaches have the advantage of massive parallelism by storing holograms as binary data pages coded by spatial light modulators of typically  $10^6$  pixels,<sup>1-4</sup> bit-oriented holographic memories also present attractive features, such as a lightweight write-read head and better compatibility with the conventional surface storage of CDs and DVDs. With such volumetric memories, holograms are spatially and (or) wavelength-multiplexed Bragg gratings inscribed at the waists of two interfering beams.<sup>5-9</sup> Bit-oriented holographic storage is commonly achieved in a counterpropagating geometry by focusing an incident beam on a sensitive medium, where it interferes with its counterpropagating reflection issued from a mirror placed on the other side of the disk.<sup>5-8</sup> During readout, the reflection on the mirror is prevented and a Bragg reflection at a given wavelength and location indicates that the corresponding bit is in the "1" state.

We propose to read out these counterpropagating bit-oriented holographic memories with homodyne detection achieved by keeping the mirror as it was during recording. The detected signal thus consists of the interference between the light diffracted by the stored gratings and the light reflected by the mirror. This detection allows an increase of the memory data transfer rate and simplifies the architecture. When the recording medium is placed directly onto a reflective layer in a Lippmann arrangement,<sup>5</sup> recording requires access to only a single side of the disk, and the necessary coherence length is reduced to twice the material thickness. The same configuration can be used during homodyne detection (Fig. 1). To detect intensity modulation due to the presence of a grating, losses have to be present in the disk structure, and the mirror reflectivity must therefore differ from 100%.

Homodyne detection enhances signal coding for the presence of a grating compared with the conventional case where only the light diffracted by the gratings is detected. This homodyne detection can be easily tackled through the following simplified approach. Plane waves are considered, and the absorption of the medium is neglected. As high capacities result in very

weak diffraction efficiencies per hologram,<sup>2,3</sup> typically between  $10^{-4}$  and  $10^{-3}$ , the attenuation of the reading beam in the medium is neglected, and the diffracted beam amplitude can be calculated using the Born approximation.<sup>10</sup> Let  $r$  be the amplitude reflectivity of the mirror and  $l$  be the thickness of the sensitive layer. Assuming that  $|r| \ll 1$ , the reflected beam is the coherent sum of the beam reflected by the mirror plus the beam diffracted by the Bragg grating. A straightforward analytical solution is thus obtained for the readout amplitude  $A_s$  returning from the incidence of  $A_i$  on the structure (Fig. 1):

$$A_s = A_i e^{2ikl} \{ r + i e^{-i\varphi} \eta_1 m \sum_{p=1}^N e^{-i(k-k_p)l} \text{sinc}[(k-k_p)l] \}, \quad (1)$$

where  $k$  is the wavenumber of the reading beam,  $k_p$  is the wavenumber of the  $p$ th inscribed wavelength among  $N$ ,  $m$  is the modulation ratio of the interference patterns, and  $\eta_1$  is the amplitude diffraction efficiency of one grating among  $N$  if it were recorded with  $m = 1$ . In a Lippmann configuration  $m$  is defined by

$$m = 2r / (1 + |r|^2). \quad (2)$$

In Eq. (1),  $\varphi$  accounts for the phase shift between a grating and its relative interference pattern so that  $\eta_1$  is real and positive. The corresponding intensity reflectivity  $R_s$  is thus given by

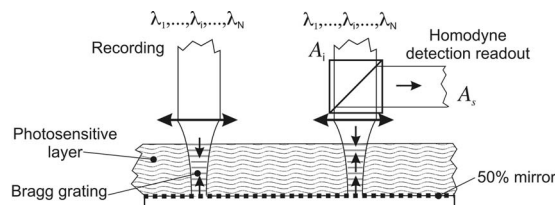


Fig. 1. Homodyne detection illustrated for a Lippmann memory

$$R_s = |r|^2 + 2|r m \eta_1| \sum_{p=1}^N \sin[(k - k_p)l - \varphi] \text{sinc}[(k - k_p)l] + |m \eta_1|^2 \left| \sum_{p=1}^N e^{-i(k-k_p)l} \text{sinc}[(k - k_p)l] \right|^2. \quad (3)$$

The readout intensity is therefore composed of an offset term due to the intensity reflected by the mirror, the  $\eta_1$  varying homodyne detection term, and the usual  $\eta_1^2$  varying intensity diffraction efficiency term. Equation (3) underlines the signal increase resulting from the homodyne detection. This increase factor is all the more important since the diffraction efficiency per hologram is weak. It can be used to enhance the data transfer rate. It is defined as the ratio of the maximum amplitude modulation of the intensity reflectivity versus the wavelength, and of the intensity diffraction efficiency  $\eta_1^2$ :

$$G = \frac{\max_{\lambda} |R_s - |r|^2|}{\eta_1^2}. \quad (4)$$

For low diffraction efficiencies (typically below 1%), this increase factor  $G$  can be computed using Eq. (3). This equation shows that  $G$  is inversely proportional to the amplitude diffraction efficiency  $\eta_1$ . In Fig. 2, for  $\eta_1 < 0.1$  and a phase shift  $\varphi = \pi/2$ , we plotted  $\eta_1 G$  versus mirror reflectivity  $|r|$ , using the approximate Eq. (3) (dashed line) and through the exact resolution of the coupled wave equations<sup>11</sup> (solid curve). Even with values as high as 0.5 for  $|r|$ , Eq. (3) still gives the right order of magnitude. Similar results are obtained for other values of phase shift  $\varphi$ . A 40% intensity reflectivity of the mirror (i.e.,  $|r| \approx 0.6$ ) maximizes  $G$ . For small diffraction efficiencies, this coefficient is about  $0.7/\eta_1$ . For instance, an increase factor of about 20 is gained for gratings whose intensity diffraction efficiency is  $10^{-3}$ .

In Fig. 3 is shown the numerically solved readout intensity reflectivity versus the wavelength for a 0.2% intensity diffraction efficiency grating inscribed at 500 nm with a 50% intensity reflectivity mirror. The sensitive layer has a thickness of 800  $\mu\text{m}$  and a refractive index of 1.5. If the grating is  $\varphi = \pi/2$  (or  $-\pi/2$ ) phase shifted from its recording interference pattern, as in photorefractive crystals, then its presence is detected by an increase (or decrease) of the signal at the Bragg wavelength. When the grating

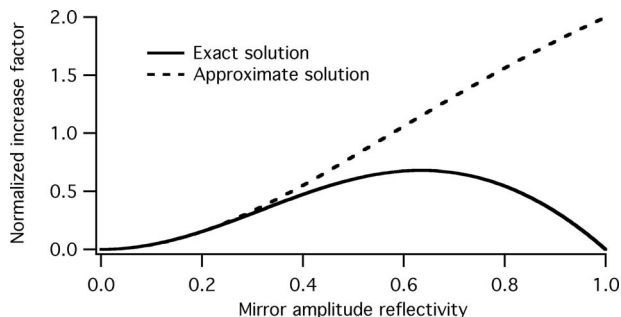


Fig. 2. Normalized increase factor versus mirror reflectivity.

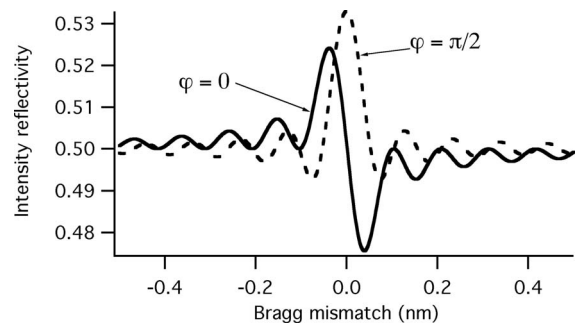


Fig. 3. Intensity reflectivity for homodyne detection versus probe wavelength for two phase shifts

phase shift is  $\varphi = 0$  or  $\pi$ , as in photopolymers, the maximum signal is detected at a wavelength slightly shifted from the Bragg wavelength.

As seen in Fig. 2, a 50% intensity reflectivity of the mirror nearly maximizes  $G$ . Such reflectivity is well adapted for further optimization of the readout geometry. The intensities reflected and transmitted by the disk can both be used as readout signals. Thus, performing balanced detection between both signals suppresses the reflection offset and makes the readout insensitive to the power fluctuations of the laser. Alternatively, such balanced detection could be done on a single side of the disk by placing a wave plate between the mirror and the recording medium. For instance, if the recording is done with a polarization parallel to one of the axes of the wave plate and if the readout is then performed with a polarization at  $45^\circ$  from them, a  $\lambda/8$  wave plate induces an additional phase shift of  $\pm\pi/2$  between the two amplitude terms of Eq. (1) for the polarization component perpendicular to the one used during recording. The reflected readout intensities along the two components would therefore be similar to the two signals depicted in Fig. 3, and balanced detection between both would produce a readout signal that is without any reflection offset and is usable at the recording wavelength whatever the phase shift  $\varphi$ . Other arrangements are possible.

An experimental demonstration has been realized to validate this homodyne detection. For this purpose, a  $\text{BaTiO}_3$  photorefractive crystal was chosen as the recording material because this rewritable material does not exhibit any optical shrinkage (e.g., neither a mean refractive index increase nor a geometrical shrinkage effect) contrary to what is seen with photopolymers. The setup used for both grating inscription and readout is depicted in Fig. 4. It involves a red spectrally filtered superluminescent diode (SLD) emitting around 680 nm with a spectral width of about 8 nm. An adjustable narrow slit in the Fourier plane of a  $4f$  system placed between two gratings makes a spectral filter. The position and the width of the slit define the wavelength and the coherence length of the beam, respectively. This beam is injected inside a single-mode polarization-maintaining fiber. At the fiber exit, this beam is collimated and sent onto the crystal. The single-mode fiber ensures that the shape of the beam onto the crystal is exactly the same for all wavelengths.

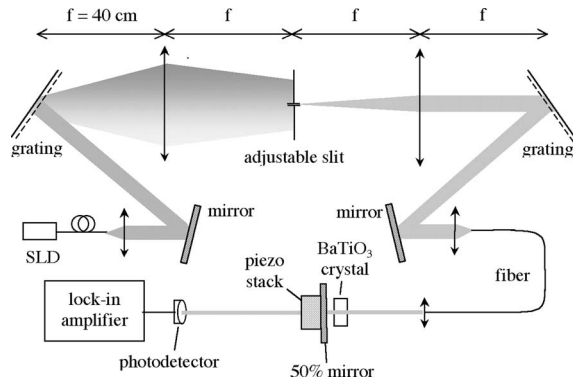


Fig. 4. Setup used to demonstrate homodyne detection of wavelength-multiplexed gratings

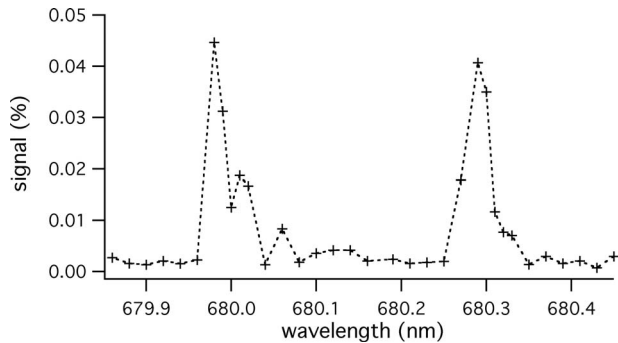


Fig. 5. Locked-in signal (% of the DC component) versus wavelength for two recorded gratings.

Placed as close as possible to a 50% intensity reflectivity mirror, the 2 mm thick BaTiO<sub>3</sub> sample was illuminated during recording by a beam of around 200 nW power and 4 mm coherence length. Two Bragg gratings were successively recorded with two different positions of the slit. For readout, the slit was narrowed further to filter a spectral width of around 10 pm and shifted at different positions over the desired wavelength range. As pointed out above, the transmitted and reflected signals are complementary. For simplicity, here we detected the transmitted signal. As the diffraction efficiencies are very weak, about  $4 \times 10^{-7}$  as explained below, the mirror is mounted on a piezo stack and detection is performed with a lock-in amplifier. The mirror was oscillated with an amplitude of about 50 nm at a frequency  $f$  close to 280 Hz, not only during readout but also while recording the gratings, to monitor their buildup in the crystal. The recording times were thus adjusted to obtain two gratings of similar strength. The experimental signal from the lock-in amplifier at frequency  $f$  is shown in Fig. 5. Two strong well-

defined peaks are effectively observed around 680.00 nm and 680.31 nm, the wavelengths chosen to record a grating. From the maximal amplitudes of the peaks, we numerically estimated the diffraction efficiency  $\eta_1^2$  of the gratings to be around  $4 \times 10^{-7}$ , which corresponds to an increase factor allowed by homodyne detection scaling to about 1000.

In this Letter we have proposed a new readout procedure adapted to bit-oriented holographic memories. The procedure consists of homodyne detection of the wave diffracted by the holograms by interfering it with a reflection of the reading beam. Such a procedure permits an increase of the readout signal that can be used to enhance the memory data transfer rate. It also simplifies the system design. We estimate the signal increase factor to be around 20 in the case of  $10^{-3}$  diffraction efficiency holograms. Such a diffraction efficiency is, however, rather an upper limit in the holographic data storage field, and lower diffraction efficiencies would result in all bigger increase factors. An experimental demonstration of homodyne detection is presented with a photorefractive crystal in a very low diffraction efficiency regime, where the increase factor reaches about 1000.

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