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Edge detection in phase-change optical data storage

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A direct mark edge detection scheme for readout in phase-change optical disk systems is described. The medium for edge detetection must be optimized to have a 90° phase difference between the amorphous mark and the crystalline space. Theoretical analysis and numerical simulation have shown that the readout signal using mark edge detection is as good as that using conventional detection of reflectivity for long marks and superior for short marks. Noise level at the output of differential edge detection is lower than that at the output of conventional detection. We also show experimental results that confirm these predictions. © *1997 American Institute of Physics.* [S0003-6951(97)02341-3]

The standard detection scheme for phase-change optical disk storage systems utilizes the reflectance difference between crystalline and amorphous marks.[1–3] The readout signal is obtained by integration of the reflected beam from the media. Here, we introduce a new readout scheme, called edge detection, for phase-change optical disk systems, which is illustrated in Fig. 1. The readout signal is the differential signal of the split detector, which relies on diffraction from mark boundaries. One advantage over the direct detection of reflectivity, here referred to as the sum detection scheme because it detects S_1+S_2, is that laser noise and media noise in the readout channel are rejected to a large extent but the signal level is comparable to that in the sum detection if the media are designed to have a phase difference of $\pi/2$ rad between the amorphous mark and the crystalline space. So a higher signal to noise ratio (SNR) is expected using edge detection than using sum detection. This method has also been proposed for readout system of magneto-optical data storage,[4,5] read-only compact devices,[6] and multilayered optical memory.[7] In magneto-optical data storage, this method was found to suffer from sensitivity to surface roughness. In this letter, we present a theoretical analysis, computer modeling, and preliminary experimental results for edge detection in phase-change data storage systems that demonstrate its high performance.

For simplicity, we restrict our analysis of diffraction from a transition between crystalline phase and amorphus phase to one dimension. The focusing lens shown in Fig. 1 is assumed to be cylindrical, with its cylinder axis parallel to the edge. Let $r_c=|r_c|\exp(i\phi_c)$ and $r_a=|r_a|\exp(i\phi_a)$ be the complex reflection coefficients of incident beam from the crystalline phase and from the amorphus phase, respectively, and assume that the state of the medium is crystalline at $x<0$ and amorphous at $x>0$. With the aid of $\mathrm{sgn}(x)=x/|x|$, the amplitude reflectivity $r(x)$ for the entire medium may be written as follows:

$$r(x)=\frac{r_a+r_c}{2}+\mathrm{sgn}(x)\frac{r_a-r_c}{2}=r_1+\mathrm{sgn}(x)r_2, \tag{1}$$

where $r_1=(r_a+r_c)/2$ and $r_2=(r_a-r_c)/2$.

The focusing lens has focal length f and numerical aperture NA. Let the amplitude distribution at the entrance pupil of the lens be uniform, and assume the total incident optical power to be unity. The amplitude distribution $A_1(x)$ at the entrance pupil is thus written as

$$A_1(x)=\sqrt{\frac{1}{2f\mathrm{NA}}}\mathrm{Re}\ ct\left(\frac{x}{2f\mathrm{NA}}\right). \tag{2}$$

The reflected distribution $A_2(x)$ at the exit pupil of the lens is the convolution of incident amplitude $A_1(x)$ and the Fourier transform of the reflection coefficient function $r(x)$, which may be expressed as

$$A_2(x)=\sqrt{\frac{1}{2f\mathrm{NA}}}\left[r_1+\frac{r_2}{\pi i}\ln\left|\frac{f\mathrm{NA}+x}{f\mathrm{NA}-x}\right|\right]\mathrm{Re}\ ct\left(\frac{x}{2f\mathrm{NA}}\right). \tag{3}$$

The differential signal ΔS between the two halves of the split detector can hence be obtained as follows:

$$\begin{aligned}\Delta S&=\int_{-\infty}^{0}|A_2(x)|^2dx-\int_{0}^{\infty}|A_2(x)|^2dx\\&=\frac{2\ \ln 2}{\pi}(r_1^*r_2-r_1r_2^*)\\&=\frac{2\ \ln 2}{\pi}|r_a||r_c|\sin(\phi_a-\phi_c).\end{aligned} \tag{4}$$

ΔS as given by Eq. (4) is maximized when $\phi_a-\phi_c=90°$, which means that, for the best results, the storage medium must be designed to have a phase difference of $\lambda/4$ (λ being wavelength of light) between the crystalline phase and the amorphous phase. Moreover, ΔS is proportional to the product of amplitude reflectivities of the amorphous mark and the crystalline space; otherwise, there is no requirement for the reflectivities of crystalline and amorphous phases. This provides great freedom in the design of the media. The magnitude of the above ΔS differs from that using sum detection by the following factor:

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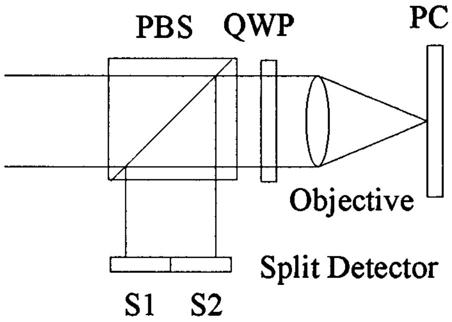

FIG. 1. Schematic diagram of the readout system. The readout signal of sum detection is equal to S_1+S_2, and that of edge detection is S_1-S_2.

$$\frac{(\Delta S)_{\text{diff}}}{(\Delta S)_{\text{sum}}}=\frac{4\ \ln 2}{\pi}\frac{|r_a||r_c|}{|r_c|^2-|r_a|^2}, \quad (5)$$

which is of the order of unity.

In the differential output of the split detector, laser noise is mostly rejected and media noise will be eliminated to a large extent. In the following analysis we assume that the disk spins at a constant velocity ν, and that the noise spectrum is obtained from an erased track. For various reasons, such as the nonuniformity of the material composition and the structure, defects, random orientations of crystallites, and material flow of the active layer, etc., there will be fluctuations in the effective reflection coefficient $r(x)$ of the erased track. We may write

$$r(x)=r_0[1+\delta(x)], \quad (6)$$

where δ is a complex coefficient representing the variations of reflectivity. We assume the spatial frequencies of these fluctuations are large enough that the amplitude distribution at the exit pupil of the lens can be expressed as the convolution of the incident amplitude and the Fourier transform of the reflection coefficient $r(x)$, which is written as follows:

$$A_3(x,t)=\sqrt{\frac{1}{2f\text{NA}}}\ \text{Re}\ ct\left(\frac{x}{2f\text{NA}}\right)r_0\left\{1+\int_{x-f\text{NA}}^{x+f\text{NA}}d\sigma F\right.$$
$$\left.\times[\delta(x)]\exp[i2\pi\sigma\nu t/(\lambda f)]\right\}, \quad (7)$$

where $F[\delta(x)]$ is the Fourier transform of the function $\delta(x)$. Ignoring the second-order terms in the noise variables, we find the differential noise $i(t)$ at the output of the split detector as follows:

$$i(t)\approx\frac{1}{2f\text{NA}}|r_0|^2\int_0^{f\text{NA}}dx\int_{x-f\text{NA}}^{x+f\text{NA}}d\sigma$$
$$\times(\exp[i2\pi\sigma\nu t/(\lambda f)]\{F[\delta^*(x)]-F[\delta(x)]\}$$
$$+\exp[-i2\pi\sigma\nu t/(\lambda f)]\{F[\delta(-x)]$$
$$-F(\delta^*(-x)]\}). \quad (8)$$

If there are no phase fluctuations in the reflection coefficient, the differential output $i(t)$ will be zero because of the properties of the Fourier transformation. This means that residual media noise at the differential output of the split detector is caused by phase fluctuations of the media's reflection coefficient. Assuming that the media noise is a stationary random process, according to the Wiener–Khinchin relation,[8] the noise power spectrum $N(f)$ as a function of frequency f is a Fourier transformation of the autocorrelation function $f(t)$ of $i(t)$:

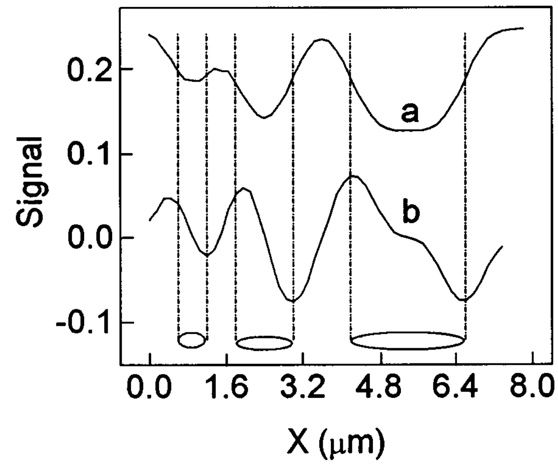

FIG. 2. Computed readout signal as function of the coordinate along the track for three successive marks. (a) Sum signal; (b) differential signal. The ellipse represents the mark, and the dashed line is a guide to the eyes.

$$N(f)=\int_{-\infty}^{\infty}f(t)\exp(-i2\pi ft)dt, \quad (9)$$

where $f(t)$ is defined as

$$f(t)=\lim_{T\to\infty}\left(\frac{1}{T}\int_{-T/2}^{T/2}i^*(t')i(t'+t)dt'\right). \quad (10)$$

Substituting Eq. (8) into Eq. (10), we find $f(t)=0$. This means that the media noise is canceled out at the differential output of the split detector to first order. In a real case, some of media noise, such as scattering, cannot be rejected using edge detection.

For numerical simulation of the readout signal we use the program DIFFRACT™[9] to simulate the signal for both the sum and the edge detection schemes. The numerical aperture of the objective lens is 0.5, and the wavelength of light is 690 nm. Figure 2 shows the computed read signal for sum detection and edge detection along a track for three successive marks. In these calculations, the marks were assumed to have the same width of 0.6 μm, and each is 0.6, 1.2, and 2.4 μm long. For sum detection [curve (a)], $|r_a|=0.25$, $|r_c|=0.5$, and a phase difference of zero is assumed; for edge detection [curve (b)], $|r_a|=|r_c|=0.5$, and a phase difference of 90° is assumed. It is seen that the readout signal in edge detection is as good as that in sum detection for long marks. For short marks, edge detection is superior to sum detection. Edge detection not only has a higher readout signal for the short mark than sum detection but it also can apparently resolve the edges of short marks. This feature will be very useful in reading densely written small marks in high density recording.

In order to confirm the above results, we made a phase-change disk for edge detection. The sample disk has quad-

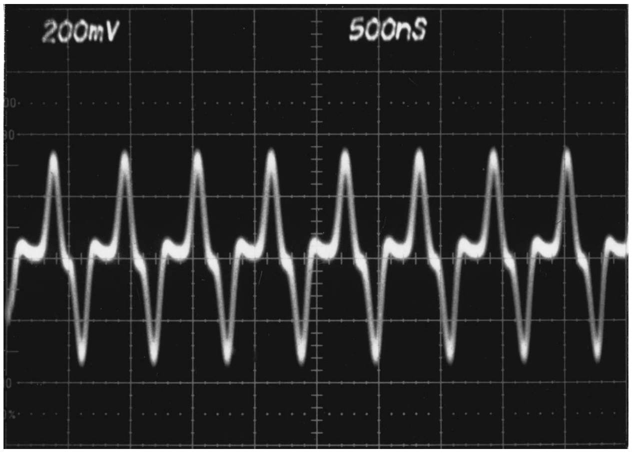

FIG. 3. Readout signal wave form of edge detection. The disk was spinning at 9.4 m/s during the write/read test. The pulse width/period for writing is 200/600 ns, and the writing power is 9 mW.

rilayer structure on a grooved polycarbonate substrate, consisting of a upper $ZnS-SiO_2$ dielectric layer (94 nm), a $Ge_2Sb_2Te_5$ phase-change recording layer (15 nm), a lower $ZnS-SiO_2$ dielectric layer (30 nm), and an Al-alloy layer (100 nm). Laser light of 690 nm for the write/read/erase test is incident on the disk from the film side. Figure 3 shows a readout signal of edge detection. The operation conditions are disk velocity $\nu=9.4$ m/s, recording frequency $f=1.67$ MHz, and duty cycle=33%. The diffraction signal from the mark's edges is clearly identified, demonstrating the performance of edge detection for readout. Figure 4 shows the measured carrier to noise ratio (CNR) as a function of recording frequency for edge detection. In these experiments, the disk's velocity $\nu=8.48$ m/s, duty cycle=45%, writing power=9 mW, and reading power=0.77 mW. More than 53 dB CNR is obtained at 5.18 MHz using mark edge detection for readout. At $f\geqslant 8$ MHz, the CNR drops, since the modulation transfer function of the system drops at higher recording frequencies. Figure 5 shows the power density spectra of signal and noise for both edge detection and sum detection, obtained by a spectrum analyzer. The carrier frequency is

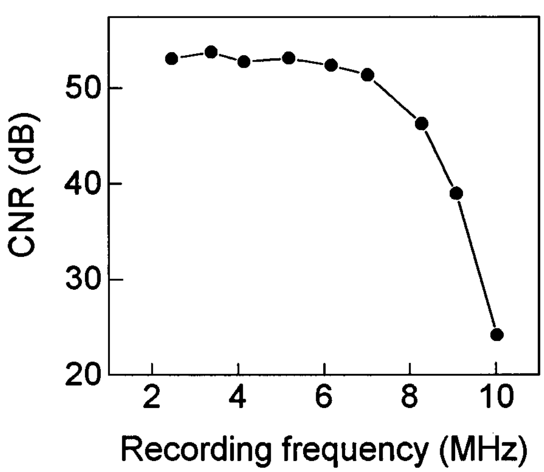

FIG. 4. CNR as a function of recording frequency using mark edge detection.

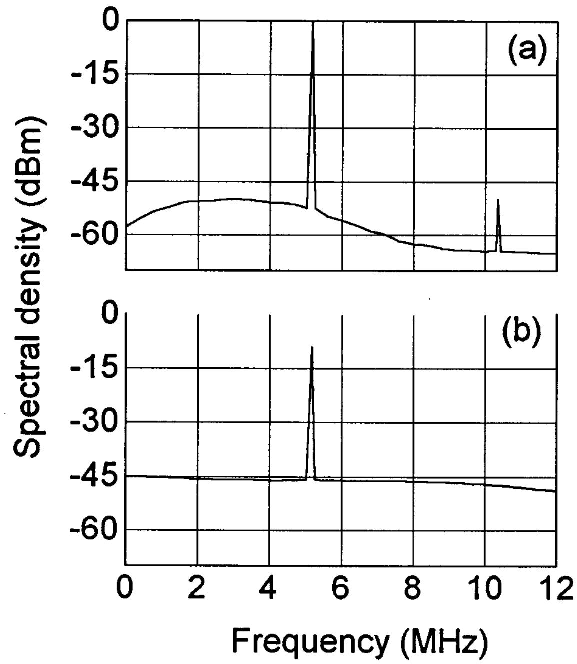

FIG. 5. Signal and noise spectra at the output of edge detection (upper frame) and sum detection (lower frame) for the 5.18 MHz carrier.

5.18 MHz. It is evident that the noise level at the output of edge detection is considerably lower than that at the output of sum detection. At $f\approx 0$ and $f\approx 12$ MHz, the noise level of edge detection is more than 10 dB lower that of sum detection. The signal level of edge detection is also much higher than that of sum detection, since the disk was optimized for edge detection not for a maximum reflectance difference between the mark and the space (sum detection).

Readout using the mark edge detection scheme was demonstrated to be feasible in phase-change optical data storage. The signal level is as good in reading long marks as that using sum detection and superior to that in reading short marks. The noise level at the differential output of the split detector is much lower than that at the output of sum detection. Moreover, the readout signal of edge detection is proportional to the product of the amplitude reflection coefficients of the amorphous mark and the crystalline space. This last feature provides much freedom in designing a medium structure to reduce overwriting jitter for mark edge recording in high density data storage.

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