Experiments Toward an Erasable Compact Disc Digital Audio System*

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Recording experiments of erasable information in magnetooptical amorphous layers on pregrooved disks are described. The recording and reading of information is done on a recorder provided with an AlGaAs laser and equipped for polarization-sensitive readout of the Kerr effect. The signal-to-noise ratio and the bit error rate of the recorded information have proved to be sufficient for half an hour of digital music according to the Compact Disc digital audio standard on a 120-mm-diameter disk (equivalent to 400 00 bit/mm^2). With only slight modifications the recorder can be used to read out normal Compact Disc records.

1 INTRODUCTION

Many research groups in the world are now investigating magnetooptical (MO) thin films for erasable storage applications. Early experiments concentrated on ferrimagnetic alloys of GdFe and GdCo [1]. Later ternary alloys have been investigated in order to optimize the magnetic and magnetooptical properties [2], [3].

System applications can be divided into two branches: low-density storage for computer applications and high-density storage for applications in the professional and consumer fields (such as digital audio).

At Philips Research Laboratories we have constructed a magnetooptical recorder to study the limits and characteristics of these storage materials from a system point of view. So far we have concentrated on alloys of GdFeTb that have been vapor deposited at Philips Research Laboratories in Hamburg. In this paper we describe the experiments we have done to establish the maximum achievable information density. Important parameters determining this figure, such as signal-to-noise ratio and bit error rate, are dealt with.

1 DESCRIPTION OF THE MAGNETOOPTICAL DISK AND THE OPTICAL RECORDER

1.1 The Magnetooptical Disk

The recording of information is done by locally heating the amorphous magnetooptical layer. The coercive force of the layer is decreased by a temperature rise, and with the aid of a small external magnetic field the magnetization of the layer is locally reversed. The influence of the internal perpendicular magnetization of the layer is to rotate the plane of polarization of plane-polarized light reflected by this layer. The rotation is positive or negative, depending on the polarity of the internal perpendicular magnetization of the layer. The top-top rotation is typically 0.7°. Fig. 1 shows a cross section of the actual magnetooptical disk. On a glass substrate a 2P (photo polymer) layer has been deposited with a groove structure in its top surface. A thin dielectric layer separates the 2P layer from the magnetooptical storage layer. It consists of an amorphous alloy of Fe, Gd, and Tb and is approximately 100 nm thick. This layer has been vapor deposited and shows an internal magnetization that is perpendicular to the surface. On top of this storage layer a protective layer is deposited. The disk is illuminated through the glass substrate. The entire disk can be sandwiched with a second glass or plastic substrate for protection against handling errors.

1.2 The Optical Recorder

The optical recorder has to perform two functions:

1) Local heating of the bit locations

2) Polarization-sensitive detection of the created magnetooptical domains.

A schematic drawing of the optics is shown in Fig. 2. The light source is a high-power AlGaAs laser with a wavelength of 850 nm. Approximately 40% of the

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light output is usefully captured by an objective lens with a numerical aperture of 0.3. The parallel beam traverses a "sun-glass" sheet polarizer, a 10% and a 25% mirror, and is focused on the disk by means of an objective with a numerical aperture of 0.6. The half-width of the light spot is slightly smaller than 1 μm. During information recording the laser is pulsed with a pulse duration of 50 ns at intervals of 250 ns. The peak power is 60 mW; due to losses in the light path, 10 mW is available in the focused light spot.

A magnetic domain generated by a single light pulse has a circular shape with a diameter of typically 1 μm. Oblong domains are generated by several light pulses being delivered at 250-ns intervals. The size of the domains is slightly influenced by the strength of the magnetic field generated by the coil behind the disk. Depending on the coercive force of the storage layer at room temperature (typically 80 kA/m), this auxiliary field varies between 10 and 20 kA/m.

Fig. 3 shows a polarization-microscope photograph of written domains in the pregrooved spiral on a disk. The domain sequence represents a typical Compact-Disc-like signal with oblong domains of discrete lengths. The minimum domain length (not the bit length) is 2 μm; the spacing between tracks is 1.7 μm.

When detecting written domains the laser is pulsed at a high frequency (13 MHz) with a duty cycle of 0.25 and a peak power of 8 mW. On the disk a quasi-continuous power of 0.3 mW is available, which is low enough not to perturb the recorded domains. The mirror with a 25% reflectivity throws reflected light onto an analyzer whose transmitting direction is almost at 90° with respect to the entrance polarizer. The rotation of the plane of polarization of the reflected light due to the magnetic domains is converted into an intensity modulation by the analyzer and detected by an avalanche detector. During recording and reading a small part of the light (10%) is coupled out to the tracking (push-pull) and focusing optics (Foucault double-wedge method). An automatic gain control is incorporated in order to compensate for the large difference in light power during recording and reading. An oscilloscope trace of the digital signal delivered by the avalanche detector is shown in Fig. 4. Local erasure of the information is done in two steps:

1) While the laser is delivering pulses every 250 ns, the external magnetic field is reversed. The whole track surface is now magnetized in the original direction.

2) New information is recorded in the normal way. It has been measured so that the information in neighboring tracks is unaffected by the erasure of a track. The signal-to-noise ratio remains unaltered.

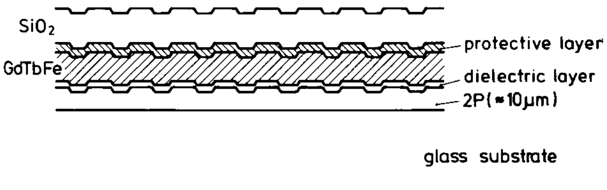


Fig. 1. Cross section of a magnetooptical disk.

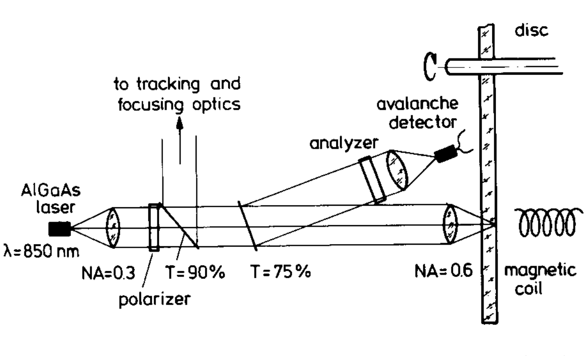


Fig. 2. Optical light path for recording and polarization-sensitive readout. When the analyzer is removed, the signals from a standard optical disk (such as a Compact Disc) can be detected.

2 SIGNAL-TO-NOISE RATIO CONSIDERATIONS

Since the magnetooptical effect is small, the signal-to-noise ratio of the detected signal is limited. Fig. 5 shows the detection arrangement consisting of an analyzer (detection angle β) that is almost crossed with respect to the incident plane of polarization. The azimuth of the plane of polarization is modulated by the magnetic domains (top-top excursion 2θ is 0.7°).

When the instantaneous azimuth of the plane of polarization is represented by an angle α, the light power after passage through the analyzer is given by

$$P(\beta, \alpha) = P_0 \sin^2 (\beta - \alpha)$$

where P_0 is the light power incident on the analyzer. Supposing α and β to be small and β not equal to 0, we approximate this expression by

$$P(\beta, \alpha) = P_0 \sin^2 \beta \left(1 - \frac{2 \sin \alpha}{\tan \beta} \right) .$$

In the case of harmonic azimuth modulation ($\alpha = \theta \cos \omega t$) we obtain the following expression for the detector current:

$$i(\beta, t) = i_0 \sin^2 \beta \left(1 - \frac{2\theta}{\tan \beta} \mu\ \mathrm{cost}\ \omega t \right)$$

where i_0 is proportional to the light power incident on the analyzer and μ (< 1) accounts for the decrease in signal amplitude due to the finite optical bandwidth. The modulation depth of the detector current is now given by

$$m = \frac{2\theta}{\tan \beta} \mu .$$

The noise current consists of several contributions:

1) Thermal noise
2) Amplifier noise
3) Dark current noise

4) Photon shot noise

5) Surface noise of the disk.

When an avalanche detector is used, the photon noise and the surface noise become predominant.

A general expression for the carrier-to-noise ratio CNR is

$$\mathrm{CNR} = \tfrac{1}{2}S^2/BN^2$$

where S is the amplitude of the signal given by

$$S = mi_{\mathrm{av}} ,$$

i_{av} denotes the average detector current, N^2 is the variance of the detector current, and B is the measuring bandwidth.

Assuming the noise to be the superposition of photon and surface noise, we obtain

$$N^2 = 2qi_{\mathrm{av}} + C\mu^2 i_{\mathrm{av}}^2$$

where q is the elementary charge and C a constant that characterizes the surface noise power. The photon noise contribution has a white spectrum, but the surface noise, as the signal itself, is affected by the optical modulation

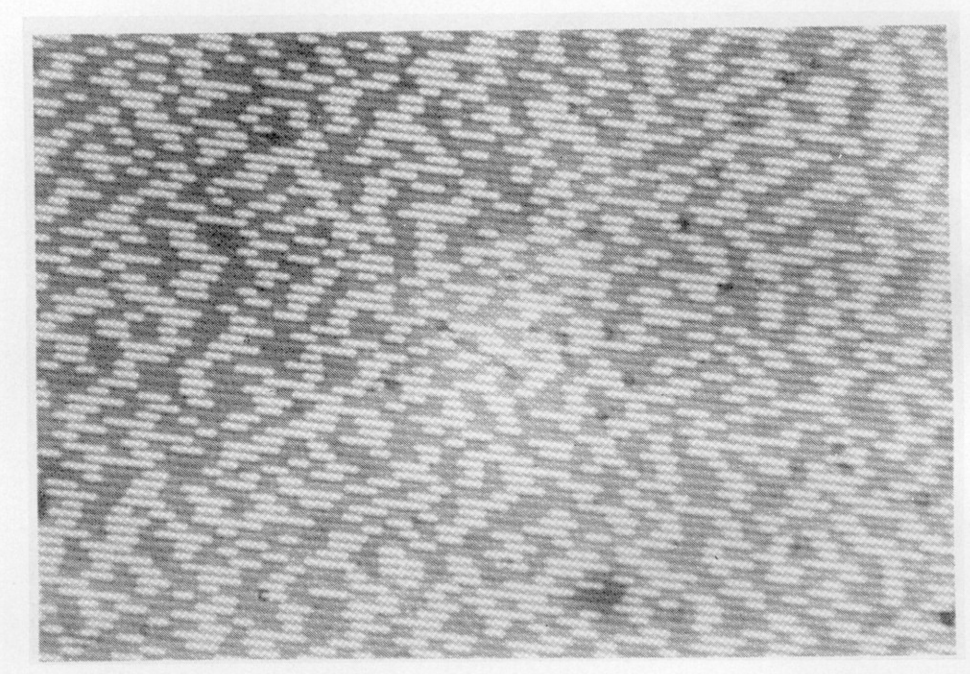


Fig. 3. The magnetic domain structure as seen in a polarization microscope with almost crossed polarizers.

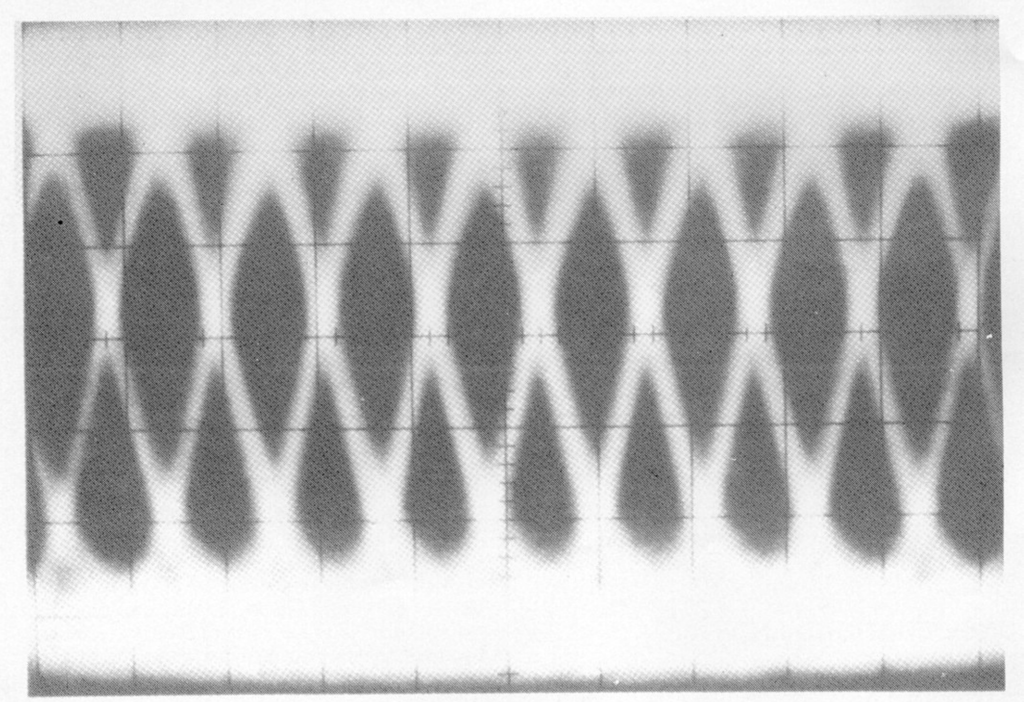


Fig. 4. Eye pattern of detected magnetic domain structure. The tangential velocity approximately equals 3 m/s.

depth μ.

The expression for the carrier-to-noise ratio becomes

$$\mathrm{CNR} = \frac{\frac{1}{2} m^2 i_{\mathrm{av}}^2}{B(2qi_{\mathrm{av}} + C\mu^2 i_{\mathrm{av}}^2)} .$$

In order to have an estimate of the surface noise contribution we can rely on data measured on VLP disks, for example [4]. In this situation photon noise can be neglected, and putting $m = \mu$, the expression for the carrier-to-noise ratio equals

$$\mathrm{CNR}_{\mathrm{VLP}} = \frac{1}{2BC} .$$

A typical value is 57 dB measured over a bandwidth of 30 kHz at a scanning velocity of 3 m/s, and the value of C can be derived from these figures.

In the case of detection of magnetic domains we obtain the following expression for the carrier-to-noise ratio:

$$\mathrm{CNR} = \frac{1}{B} \frac{(2\theta^2\mu^2/\tan^2\beta)\, i_{\mathrm{av}}}{2q + C\mu^2 i_{\mathrm{av}}}$$

The average detector current depends on the light power incident on the detector and equals

$$i_{\mathrm{av}} = \frac{P_{\mathrm{L}}}{h\nu} \eta q \sin^2\beta$$

where $h\nu$ is the photon energy and η the quantum efficiency of the dectector (≈ 1).

The light power incident on the analyzer equals

$$P_{\mathrm{L}} = RTP_0$$

where P_0 is the average power (0.3 mW) incident on the disk, T the transmittance of the light path from the disk to the analyzer (typically 0.15), and R the reflectivity of the storage layer (50%).

With a measuring bandwidth of 10 kHz the final expression for the carrier-to-noise ratio becomes ($\mu \approx 1$)

$$\mathrm{CNR} = \frac{3.3 \times 10^5 \cos^2\beta}{1 + 4.5 \times 10^{13} C \sin^2\beta} .$$

In Fig. 6 this theoretical carrier-to-noise ratio is shown as a function of the analyzer angle β. The carrier-to-noise ratio is depicted for several values of the disk surface noise. The optimum for a standard disk (curve c) is seen to be 50 dB and is reached at analyzer angles close to 0°.

3 DESIGN CONSIDERATIONS AND MODULATION SYSTEMS

Modulation systems are normally used to adapt the incoming binary data stream to the particular characteristics of the recording medium. The main target is space efficiency, that is, to obtain the highest information density permitted by the limiting characteristics of the recording channel. Modulation systems, sometimes called channel codes, can be designed to match a wide scale of specific requirements. For example, a channel code can be so designed that only domains of unit diameter are recorded (domain position modulation). Other channel codes transform the data stream in such a way that the information is contained in the lengths and the position of the magnetic domains. All these channel codes have their particular pros and cons, which can only be determined by many experiments. During our experiments with the magnetooptical storage medium we studied the behavior of a large class of modulation systems. As an example of domain-length modulation we studied the class of so-called run-length-limited sequences.

A binary string of bits is defined as run-length limited if the number of consecutive 1s (or 0s) is bounded between certain minimum and maximum values. For example, the Compact Disc code EFM is so designed that only strings of at least three and at most eleven consecutive bits of the same polarity are allowed as a

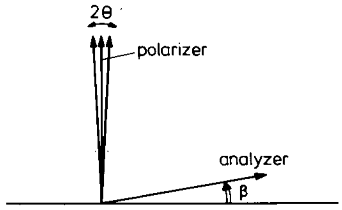


Fig. 5. Orientation of polarizer and analyzer for the detection of magnetic domains. The domains induce an azimuth modulation of the plane of polarization with an amplitude of 2θ.

Numerical data on surface noise
curve a: CNR infinite
curve b: CNR = 60 dB
curve c: CNR = 57 dB
measured over 30 kHz at tangential speed of 3 m/s

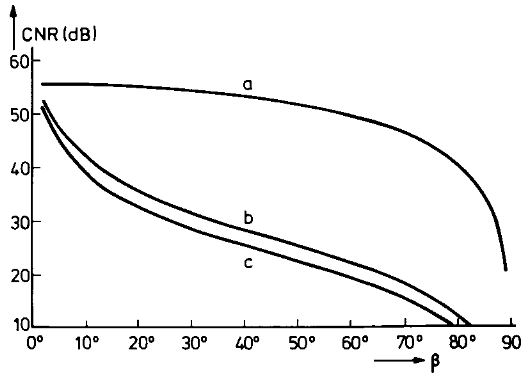


Fig. 6. Theoretical carrier-to-noise ratio of signal due to magnetic domains. Curve a applies to a perfect disk without surface noise. The noise is due only to the shot noise of the photons. Curves b and c show the influence of the surface noise of a disk. The optimum detection angle is seen to be close to 0° (complete extinction). A practical limit is 2–3° because otherwise the detection becomes nonlinear (second-harmonic distortion).

modulator output. The backgrounds to the choice of certain maximum and minimum run lengths are briefly outlined in the following. If the clock regeneration is derived from the actual readout data, which is normally the case, then level transitions yield the synchronizing information. A small maximum distance between transitions benefits the worst-case clock regeneration. A large minimum run length decreases the maximum frequency of the modulation stream, so that the bandwidth requirements of the channel may be reduced.

State-of-the-art high-power solid-state lasers have a limited time during which they can emit a light pulse, and they can only be used in the pulsed mode, which naturally leads to modulation systems using (unity) domain position modulation. We can, however, use domain-length modulation, with its much higher space efficiency, if we record the domain lengths as overlapping unit domains.

In Fig. 7(a) we have depicted as an example a binary modulation stream that has to be recorded on the disk. T is a channel bit time. The domain lengths are integral multiples i of T, with certain minimum and maximum bounds of i. By electronic means we derive a pulse sequence [Fig. 7(b)]. If the signal in Fig. 7(a) is high, then a domain has to be recorded, resulting in the visualized domain pattern plotted in Fig. 7(c).

Designing and building real-time (de)modulators is a time-consuming activity, especially when a wide range of codes has to be tested. We proceeded therefore in a way used before in experiments with a Te-based storage medium. We programmed a number of PROMs so that they contained short binary sequences satisfying a certain modulation rule. All PROMs contained a frame sync pattern of 27 bits and a sequence of 561 bits satisfying the modulation rule. The frame sync pattern was identical in all experiments. The PROMs were periodically read out with a clock frequency of 4 MHz. The angular velocity of the disk was adjusted to the desired tangential information density. After writing one or more tracks, we read out using the repeat track feature. The signal from the avalanche detector was further electronically processed (digitized, clock recovery, frame sync, etc.). The binary processed signal was now compared with the output of a PROM containing the original sequence. The PROM was synchronized by the frame sync pulses derived from the recovered information. In this way we were able to generate a sequence of bit errors that could be investigated for its statistics, such as number of single-bit errors, average error burst length, and so on.

4 EXPERIMENTAL RESULTS

In this section we describe some of the experimental results obtained during our investigations. The main goal of all experiments was to characterize the magnetooptical channel establishing the maximum reliable information capacity. First we studied the noise levels and the main noise sources. Further we studied the bit error rates, that is, the ratio of bits that are in error to the total number of bits that are read out. A new tool to measure characteristic properties of the magnetooptical channel is the pulse-length distribution measurement described in Sec. 4.3.

4.1 Measurement of Carrier-to-Noise Ratio

We recorded a pure frequency of 500 kHz on the disk at different linear velocities. The frequency was chosen equal to 500 kHz because the signal power of the EFM modulation system is maximum in this frequency region. We measured the different noise levels relative to the detected signal power, always integrating over a bandwidth of 10 kHz. The noise level that determines the final carrier-to-noise ratio is due to surface roughness of the disk. In nonrecorded regions and equally on an aluminum-coated disk this noise level is identical. A characteristic value is −44 dB when the scanning velocity is 3.25 m/s (see Fig. 8). As should be expected in the case of surface noise, the noise level increases when the tangential velocity is decreased. Other noise sources are photon noise, amplifier noise, and dark current noises. The photon noise can be measured separately from disk surface noise when the disk is not rotating. This noise level is −48 dB with respect to the signal. Dark current noise and amplifier noise are at a level of at least −56 dB.

4.2. Measurement of Bit Error Rates

Following the procedure described in Sec. 4, we have detected bit error rates by comparing a detected bit sequence with the originally recorded sequence. An important parameter is the linear scan velocity that influences the carrier-to-noise ratio and consequently the bit error rate. The measured 44-dB carrier-to-noise ratio yields a bit error rate of 10^{-5} or less, and the few

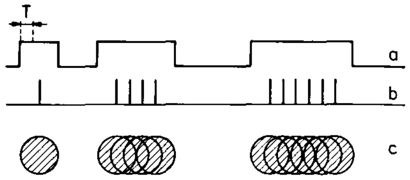


Fig. 7. Electronic translation of a pulse-width modulation into a signal usable for a pulsed mode laser.

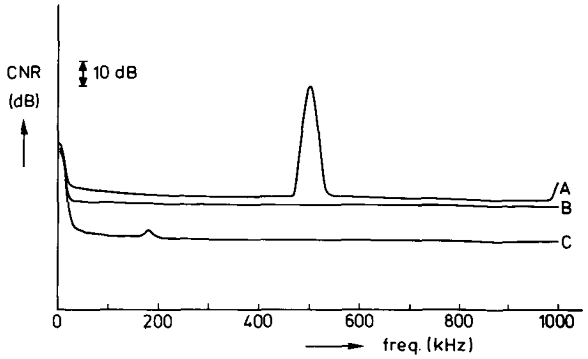


Fig. 8. Measured carrier-to-noise ratio (bandwidth 10 kHz) of signal due to magnetic domains. The upper noise level is due to medium noise.

detected errors are nearly all fixed in position on the disk and are thus due to disk imperfections. At lower scan velocities the carrier-to-noise ratio slightly decreases. A more serious consequence of the lower velocity is the asymmetry in the recorded signal due to the finite minimum length of a recorded domain. By deleting the first laser pulse during recording from each sequence of 3, 4, . . . , 11 pulses we can establish a new recording optimum at a reduced linear velocity. The experiments showed that at a tangential speed of 2.4 m/s a bit error rate of 10^{-4} is still possible.

4.3 Measurement of Pulse-Length Distribution

As stated in Sec. 4.2, the bit error rate is a measure of the quality of the system, the disk included. The bit error rate is not always an adequate measure of the system performance. Measuring the electrical pulse widths in the disk playback channel and displaying their distribution can give insight into characteristics of the system.

The pulse-length distribution system measures, as its name indicates, the distribution of the lengths of the pulses (distances between transitions). The system generates plots as depicted in Fig. 9. Each plot is divided into an upper and a lower part depicting the length distributions of the domains depending on polarity. To calibrate the horizontal axis of the plots, a pulse-length distribution of an EFM sequence was measured directly, without the disk channel [see Fig. 9(a)].

Some interesting properties appear in those plots. As mentioned, a serious consequence of a deviation from the correct speed is that the symmetry is disturbed. The plot of Fig. 9(c) was recorded at approximately the nominal tangential velocity (3.25 m/s) and the plots of fig. 9(b) and (d) with velocities of 4.0 and 2.5 m/s, respectively. To correct for the asymmetry, one (or more) of the successive laser pulses can be deleted. Fig. 9(h) and (i) depicts the pulse-length distribution without and with this asymmetry correction. The upper and lower parts of the graphs shift with respect to each other. As a consequence of an increasing density the intersymbol interference (or tangential crosstalk) increases. Due to this phenonemon the bell-shaped area centered around t_1, t_3, t_5, etc. [Fig. 9(b) and (h)] spreads out and the area centered around t_2, t_4, etc., is filled up [see Fig. 9(d), (f), and (h) for tangential velocities of 2.5, 2.25, and 2 m/s, respectively]. This results in an unreliable bit length decision, and hence the bit error rate increases.

4.4 Compact Disc Digital Audio System

Initially bit sequences generated by a PROM were used as a data source. To explore the possibilities of the magnetooptical system channel we also investigated the use of Compact Disc music as a data source [5]. The preceding experiments showed that the CD channel code EFM, as described in Sec. 4, was quite feasible. A standard Compact Disc consumer player was used to deliver the digitally encoded music.

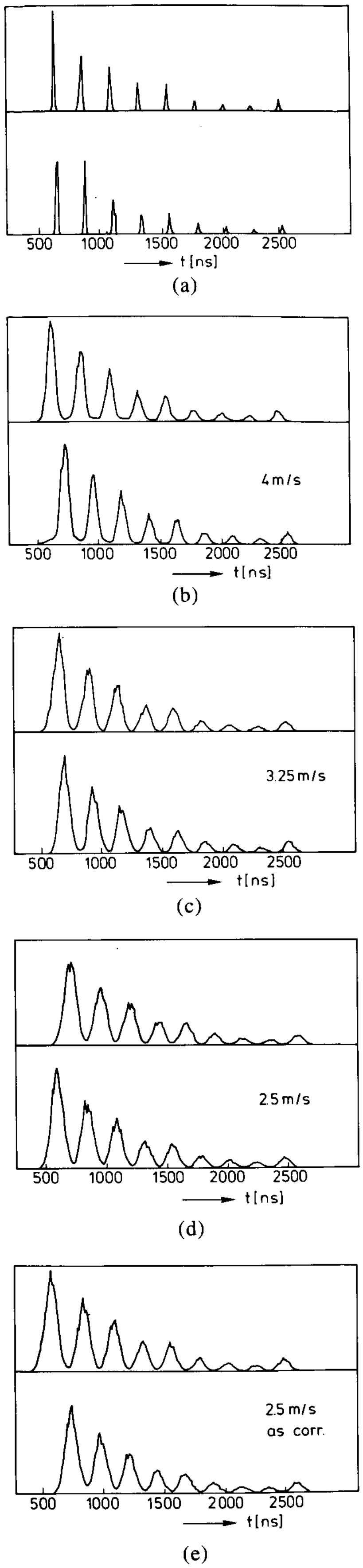
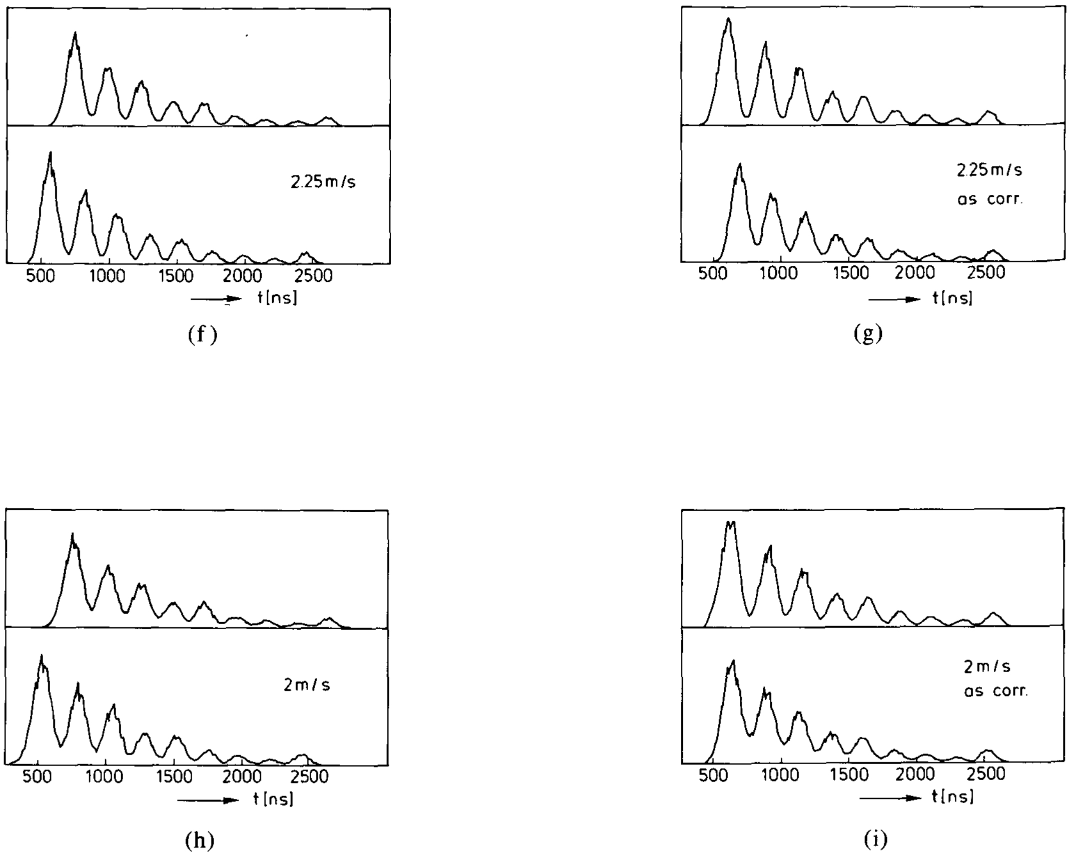


Fig. 9. Pulse-length distribution as a function of linear density (arbitrary vertical axis) for different tangential speeds. (a) Calibration of horizontal scale. The distance between tops corresponds to 231 ns. (b) 4 m/s. (c) 3.25 m/s. (d) 2.5 m/s. (e) 2.5 m/s, one pulse deleted for asymmetry correction.



(f) (g) (h) (i)

Fig. 9. Pulse-length distribution as a function of linear density (arbitrary vertical axis) for different tangential speeds. (f) 2.25 m/s. (g) 2.25 m/s, one pulse deleted for asymmetry correction. (h) 2 m/s. (i) 2 m/s, one pulse deleted.

The high-frequency signal from the Compact Disc's photodiode was electronically processed and fed to the magnetooptical recorder.

With a linear bit density of 40% of the Compact Disc density the music was recorded and reproduced with the same performance as obtained from a Compact Disc player.

The experimental setup for recording the music is equally suited for playing back standard compact disks manufactured for a consumer Compact Disc player, only the analyzer sheet must be removed.

5 CONCLUSIONS

Thermomagnetic recording on pregrooved disks (track spacing 1.7 μm) has been demonstrated with domain dimensions in the micrometer range. The signal-to-noise ratio of the detected signal is sufficient for an error-free recovery of a digital music signal according to the Compact Disc standard. The information density in the track direction is 40% of the density on a Compact Disc. At the present time the density is limited by disk surface roughness and not by random variations in domain dimensions.

Erasure of recorded domains has been accomplished in two stages (one erase step and one writing step). Preliminary experiments with real-time overwriting by modulating the external magnetic field with a digital music signal (up to 2 MHz) look promising.

6 ACKNOWLEDGMENT

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7 REFERENCES

[1] P. Chaudhari, J. J. Cuomo, and R. J. Gambino, *IBM J. Res. Dev.*, vol. 17, p. 66 (1973).

[2] M. Urner-Wille, *J. Mag. Mat.*, pp. 15–18 (1980). 1339–1340.

[3] M. Urner-Wille, P. Hansen, and K. Witter, *IEEE Trans. Magn.*, vol. MAG-16, no. 5 (1980).

[4] J. P. J. Heemskerk, *Appl. Opt.*, vol. 17, p. 2007 (1978).

[5] L. B. Vries, K. A. Immink, J. G. Nijboer, H. Hoeve, J. Timmermans, L. M. Driessen, T. T. Doi, K. Odaka, S. Furukawa, I. K. Iwamoto, Y. Sako, H. Ogawa, and T. Itoh, "The Digital Compact Disk: Modulation and Error-Correction Schemes," presented at the 67th Convention of the Audio Engineering Society, *J. Audio Eng. Soc.* (*Abstracts*), vol. 28, p. 931 (1980 Dec.), preprint 1674.

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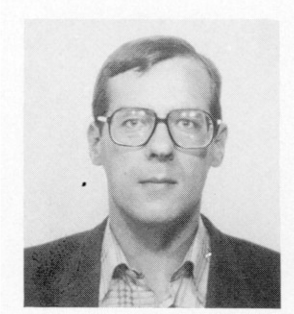

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He then joined the measurement and control group of the Philips Laboratories to do research on servo systems for the laser video system.

In 1979 he joined the optical recording group working on channel codes for optical disk systems, in particular the digital audio Compact Disc system.

Mr. Immink holds several patents in the fields of servo, acoustical, and modulation systems.

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Joseph Braat graduated from Delft Technical University in 1970 and wrote his thesis during a three-year stay at the French Institut d'Optique in Paris. The subject was holography using spatially incoherent light. In 1973 he joined the optics group of the Philips Research Laboratories in Eindhoven and became active in the field of optical recording, scanning, microscopy, and lens design.