Second-harmonic magnetoresistive imaging to authenticate and recover data from magnetic storage media

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Abstract. *A scanning magnetoresistive (MR) microscope is developed for high-resolution imaging of magnetic tapes and digital media. Second-harmonic detection is used to remove thermal anomalies. We are able to image sufficient lengths of tape for authentication purposes and for data recovery from damaged samples. The second-harmonic technique provides high-contrast magnetic images of the magnetic storage media using high-resolution MR sensors from commercial hard disk drives. These images can be directly converted into the originally recorded analog audio waveforms or digital data.* [DOI: 10.1117/1.1866150]

1 Introduction

The imaging of magnetic patterns on tape media is important for forensic analysis and data recovery from damaged samples. These images are frequently used to authenticate evidence in criminal cases. The commonly used method of obtaining this information is to apply a fluid that has a suspension of small magnetic particles, i.e., ''ferrofluid,'' to the tape, to allow the fluid to evaporate, and to image the resulting patterns of particles with an optical microscope.[1–3] However, the ferrofluid imaging techniques suffers from two main problems. First, the sign of the magnetic field is not indicated, hence the signal cannot be converted directly into the original audio or digital waveforms. Second, while coarse-grained ferrofluids are effective for analog media, the fine-grained ferrofluids required to image higher density digital data often cause permanent spurious errors.

Here we present a newly developed imaging technique, magnetoresistive (MR) microscopy that is based on technology developed for the data storage industry.[4] The advantages of this technique are that it gives the sign of the magnetic field (hence analog waveforms can be recovered), it has a high dynamic range, the data are acquired and analyzed by a computer, and it is noninvasive. A wide range of samples have been studied including analog cassette tapes with read/write head stop events, analog video tapes, digital audio tapes, 3.5- and 5.25-in. floppy disks,

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computer hard disks, and tape segments from airline flight data recorders. In this paper, we describe the imaging technique, show representative images, and demonstrate that both analog audio waveforms and digital data can be recovered.

2 Apparatus

MR sensors have become a key element in the magnetic data storage industry over the past 30 years. MR sensors are comprised of a strip of magnetic material, usually a nickel-iron alloy, that changes resistance in an applied magnetic field. Two advantages of MR sensors are that the signal is independent of velocity (as opposed to an inductive sensor) and the strip can be scaled down to submicrometer dimensions. Research into the use of MR elements for streaming digital tape storage began in the mid-1970s, and they were in mass production by the mid-1980s. This type of sensor was incorporated into magnetic hard disk drives in the early 1990s, and advances in this technology have been a major part of the increase in storage capacity of hard disk drives for computers seen over the past decade.

The sensors used here rely on the anisotropic MR (AMR) effect. The maximum resistance change of these sensors in saturation is about 1% when a magnetic field is applied perpendicular to a current flow.[5] A constant direct current (dc) bias current is applied to the sensor in most applications, enabling the resistance to be measured according to Ohm's law. For this paper, we use self-biased AMR heads from hard disk drives that were commercially available in the mid-1990s. These self-biased sensors rely on the magnetic field generated by the bias current to linearize the response of the sensor. One obstacle to the use of these elements is their inherent temperature sensitivity. As the devices are scaled down, the heat capacity is also reduced. Therefore, any dirt or irregularity on the storage media that comes into contact with the sensor can cause a jump in the resistance, i.e., a thermal asperity. It has been shown that thermal asperities can be rejected by using an alternating current (ac) bias.[6] For ac bias at a some frequency f, the magnetic field from the sample modulates the amplitude of the sensor response at $2f$. This is due to the fact that the interaction of the bias current and magnetic moment of the sample is independent of the sign of the bias current. This is referred to as second-harmonic detection, and allows for low noise imaging of the magnetic fields above a magnetic storage tape, floppy disk, or hard disk. The method of data acquisition used with the MR microscope involves scanning an MR sensor over the sample many times to build an image. A drawing of the sensor is shown in Fig. 1. The suspension is a flexible strip that enables the highly polished slider to press on the sample with very low, constant force. The sensor is mounted on the front edge of the slider, and is in contact with the surface. The sensor measures the vertical component of the magnetic field. The intrinsic spatial resolution of the sensors is 0.05 μm in the scan direction (along the suspension, as shown in Fig. 1) and 5 μm laterally. The assembly is mounted on a two-axis translation stage. This enables it to be scanned back and forth and side to side. The motion is controlled by a computer connected to servomotor-driven micrometers. The range of the translation can be up to 10 cm in either direction. The sensor position is monitored by the computer using quadrature encoders (0.6-μm resolution) mounted to the micrometer shafts.

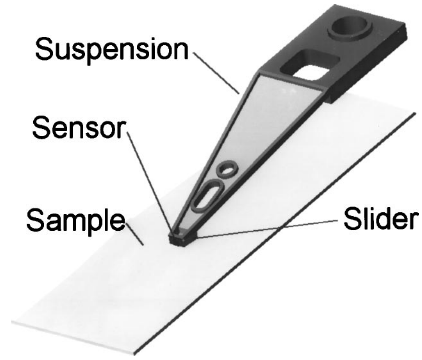

Fig. 1 Head assembly (not to scale) from hard disk drive that is used in the imaging technique. Elements include suspension, slider, and the MR sensor element.

The media sample is held in place using a micro-channel plate vacuum chuck mounted on a servomotor controlled vertical translation stage. (The microchannel plate is a glass plate with many holes (i.e., channels) having 10-μm diameter and 15-μm spacing. The microchannel plate technology was developed for electron amplification plates used in visible light image intensifiers. We found that these plates make excellent vacuum chucks for magnetic tape media.) This enables manual loading of samples into the imaging apparatus. The sample is then raised to the slider to initiate the imaging process. Direct contact of the sample and head can be prevented by covering the sample with a thin sheet (3 to 25 μm) of polyester. We observe a 6-dB voltage drop in signal using a 13-μm polyester sheet, with an additional 6 dB for every doubling of the thickness thereafter. These data are shown in Fig. 2 for a test cassette tape sample. We can see that the 3-μm sheet does not degrade the performance of the system significantly. The polyester is used only to prevent scraping or damage to delicate forensic evidence. The total force exerted by the head onto the tape is less than 10 mN $(1g)$. Over the area of the sliding surface this gives a pressure of 3 kPa. This pressure, especially applied through an overlying film, is much less than what would make any physical changes to the underlying tape. The pressure is an order of magnitude less than that applied

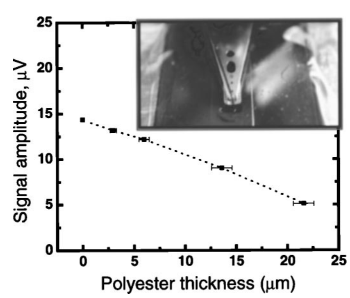

Fig. 2 Typical dependence of the second-harmonic signal amplitude at 20 kHz as a function of the polyester sheet thickness. The amplitude of the bias current was 3.5 mA. The signal was obtained from a 560-Hz test tone recorded on a commercial analog audio cassette tape sample. The inset shows photograph of the tape being scanned with the polyester film covering it. The relaxed areas of the polyester are evident at the edges of the vacuum chuck (dark area).

in a cassette tape playback system. We tested this by observing that when the head is pressed against the felt of a standard cassette, the deflection (0.25 ± 0.05 mm) is a fraction of that when the tape is mounted into a typical player (2.5 ± 0.1 mm).

The electronics for the system consists of an alternating current bias supply, a Wheatstone bridge, and a lock-in amplifier. The bridge is balanced so the first harmonic ($1f=10\,\mathrm{kHz}$) signal from ac bias is minimized. The $2f$ signal at 20 kHz is then detected by the lock-in amplifier. The design point for the current bias of the AMR element is 12 mA and the resistance is typically 50 Ω. The magnetic field due to this current at the media is less than 5 Oe, and therefore will not affect the magnetic data written on the tape. In addition, the AMR head is designed with a ''soft adjacent layer'' that closes the flux of the magnetic element. For the resistive noise analysis, at 20 kHz we are above the majority of the $1/f$ noise for metal film resistors and magneto-resistive elements.[7,8] Therefore, the measurement noise floor is determined by the electronic noise in the resistor and the Barkhausen noise of the magnetic sensor. The electronics noise is dominated by the shot and Johnson noise, which, for these resistances, are $3\times10^{-3}\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ and $1\times10^{-3}\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$, respectively. Added in quadrature, the intrinsic electronics noise level is less than $4\times10^{-3}\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$. With a 10-ms time constant, the expected noise level is approximately 0.04 μV. From a cassette tape sample, a signal of about 50 μV is typically measured (this signal level is expected from these shielded AMR elements because this type of commercial sensor is designed to detect very narrow transitions on a hard disk drive; we are currently experimenting with unshielded sensors and expect an order of magnitude larger signal), resulting in an electronics signal-to-noise ratio (SNR) close to 62 dB. In addition, when the MR sensors are operated with an ac bias[6] the magnetic noise has been observed to reduce the SNR by 10 to 15 dB, giving an expected SNR of 45 to 50 dB. This matches closely to our observed experimental SNR levels.

The total time to acquire the image is determined by the resolution required and the time constant of the electronics. This technique is capable of very high resolution because the heads are designed to detect transitions less than 0.1 μm. This would correspond to frequency bandwidth on a cassette of greater than 100 kHz. For authenticity analysis, however, samples every 25 μm along the length of the tape are sufficient. To recover an audio signal with bandwidth up to 4 kHz a sampling rate of 8 kHz is required. Since standard analog audio cassette tapes are recorded at 4.76 cm/s ($1\frac{7}{8}=1.875$: in./s), this sample rate translates to 6 μm sample spacing along the scan direction. Typical total scan times for an image of 1 s of cassette tape can take anywhere from 10 to 60 min, depending on the desired resolution and the number of scans across the width of the tape.

3 Evidence Authentication

In the forensics field, magnetic media are commonly used and are frequently admitted as evidence in court proceedings. Occasionally, this evidence is challenged and a determination is sought to discover if the tape is authentic, i.e., ''has this tape been altered; is it original or a copy?'' Although ferrofluid continues to be an effective tool to determine the authenticity of analog audio cassette tapes, newer recording formats and modern recording systems require imaging techniques with an improved SNR and a higher contrast. In addition, recovery of analog waveform data directly from the scanned magnetic image greatly enhances the state of the art in forensic audio.

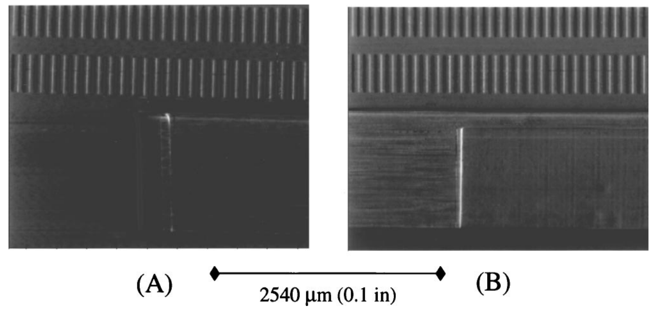

Fig. 3 Images from a test audio tape: (a) an erase head stop event and (b) the corresponding write head stop event.

Analog audio cassette tape recorders must erase, record, and play. Some specialized decks use separate heads for each of these functions but most decks use a combined play/record head. Most machines leave distinctive recording features that can be revealed on imaging the magnetic patterns left on the tape. More expensive, professional quality recorders are designed to minimize any magnetic artifacts of the recording process. In any case, if these features can be imaged, then they can be used to determine the authenticity of the recording. When recording events occur, i.e., starts, stops, erasures, and overrecordings, an examiner can determine whether the recording is original, continuous, and unaltered. For example, Fig. 3 shows images from a test audio tape. This tape was recorded on one side (the top) in stereo with a 400-Hz tone on both the left and right channels. On the other side (bottom), a mono recording was stopped on virgin tape, with no signal input to the recorder. The tape would be flowing from right to left in these images. In Fig. 3(a), the magnetic stop mark of the erase head can be seen as vertical dark and bright stripes. These correspond to positive and negative magnetic field out of the plane of the tape. In addition, there is a horizontal magnetic mark along the center of the tape that is made by the erase head. In Fig. 3(b), the magnetic stop mark of the write head can be seen as a bright vertical stripe. The difference between these two events can be clearly seen. Forensic audio experts are often able to relate these features to various parameters of the head that created them.

In addition, the magnetic texture of the tape can be observed. For example, the virgin tape to the left of the erase head stop mark in Fig. 3(a) is significantly smoother than the erased tape [to the right of the erase head stop mark in Fig. 3(a) and left of the write head stop mark in Fig. 3(b)]. The recorded area of the tape, to the right of the write head stop event in Fig. 3(b) is also much smoother than the erased area. To illustrate this fact more clearly, a 3-D rendering of the data from Fig. 3(b) is shown in Fig. 4. This rendering shows a profile of the magnetic field along the surface of the tape. It is useful because it enables one to identify the various regions of the tape. For example, we

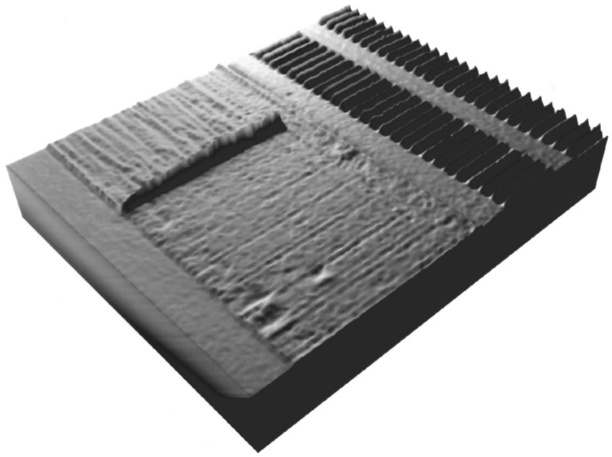

Fig. 4 Three-dimensional rendering of the write head stop event from Fig. 3(b). The height of the surface corresponds to the strength of the magnetic field.

can see that there are striations left by the write head that distinguish it from the virgin tape areas between the tracks.

To compare this technique directly with the ferrofluid imaging, we imaged the same spot on another test tape with both methods. Figure 5(a) shows an erase head stop event imaged with the ferrofluid. Figure 5(b) shows an MR image of the same event after the ferrofluid was cleaned off. This image was made without using the polyester protection layer. The image demonstrates the higher resolution of the same features already noted; however, there are also slightly darker streaks apparent that go the full length of the scan. These may be due to either the presence of intermittent contamination of the sensor (from ferrofluid) or small offset shifts in the $2f$ signal from the magnetic modulation.

Important new features in the MR images are the clarity of track edges, texture difference between the virgin versus nonvirgin areas, and the fact that the features left by the heads may be either darker or lighter than the background, whereas the corresponding features in ferrofluid images are always lighter. The first two points indicate that MR imaging may eventually assist the forensic examiner in characterizing with more certainty the type of recorder used. The last point demonstrates that the MR technique measures both the magnitude and direction of the magnetic field above the sample while the ferrofluid indicates only the magnitude. In this particular demonstration, in fact, we discovered from the MR image that the two quarter-width

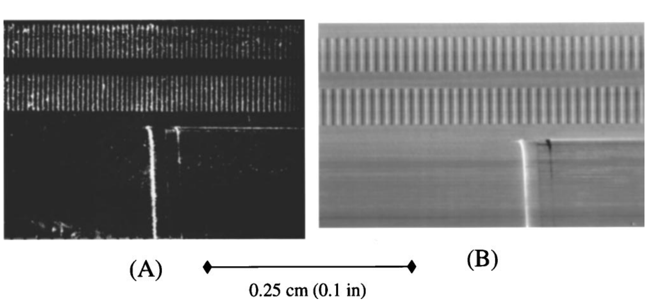

Fig. 5 Analog audio cassette tape sample imaged using (a) the conventional ferrofluid technique and (b) a MR microscope.

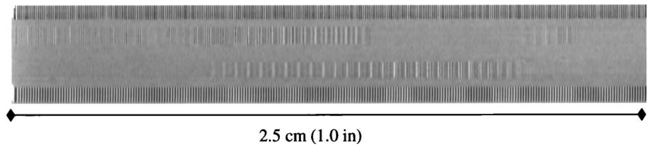

Fig. 6 Image of analog audio cassette tape sample with the word "FBI" and a 560-Hz test tone recorded on the inner and outer tracks, respectively (side A, top, going from right to left). The word "NIST" and a 400-Hz test tone are recorded on the inner and outer tracks, respectively (side B, bottom, going left to right).

heads were recording signals 180 deg out of phase with each other. This can be seen in Fig. 5, where the bright versus dark lines of the top two tracks of Fig. 5(b) are transposed, while same two tracks in Fig. 5(a) appear to be identical. Therefore, this is another feature of a recording that cannot be detected with ferrofluid.

4 Analog Waveform Recovery

As discussed in Sec. 3, a drawback of the ferrofluid technique is that the particles accumulate at all magnetic transitions, regardless of the polarity of the transition. Therefore, the signal cannot be translated directly into an audio waveform without making assumptions about how the magnetic field changed. The MR microscope, however, maps both the direction and strength of the magnetic field. Figure 6 shows an image of 2.5 cm of audio cassette tape that has both a voice and test signal recorded. To demonstrate that the audio waveform can be obtained from this image, in Fig. 7(a) we show a single scan from the "F B I" track of Fig. 6. The bottom panel shows the audio wave that was sent to the recorder from the microphone. An expansion of the recorded and measured waveforms in the region of the letter "I" is shown in Fig. 7(b). The similarity of these two waveforms is evident in spite of the fact that no equalization has been applied to the signal from the tape recording. When the signal from the MR microscope is sent directly to an audio speaker, the voice of the person speaking can be clearly identified.

The main difference between the data from the top and bottom panels of Fig. 7(a) is the lower SNR in the MR microscope linescan ($\approx$25 dB). This noise is a combination of the media noise and the intrinsic noise in the MR element. The media noise is due to the fact that the line scan is a small fraction (0.8%) of the width of the track. When adjacent scans are averaged, we find that the linear voltage SNR increases as the square root of the number of scans, as expected for random noise. In decibels, the SNR increases as $10\log_{10}$ (number of scans averaged). The maximum number of independent line scans across each track at this resolution is 120, hence the SNR will increase from about 25 dB to $25+10\log_{10}(120)=46\,\text{dB}$ when these linescans are averaged. This is a typical SNR number for an analog audio cassette tape recording.

5 Digital Data Recovery

For digital media, the MR technique provides improved SNR, higher resolution, and no requirement for ferrofluid, which has been found to contaminate most digital playback systems. Figure 8 shows an image of computer data recorded on a helical-scan digital audio tape (DAT). Because

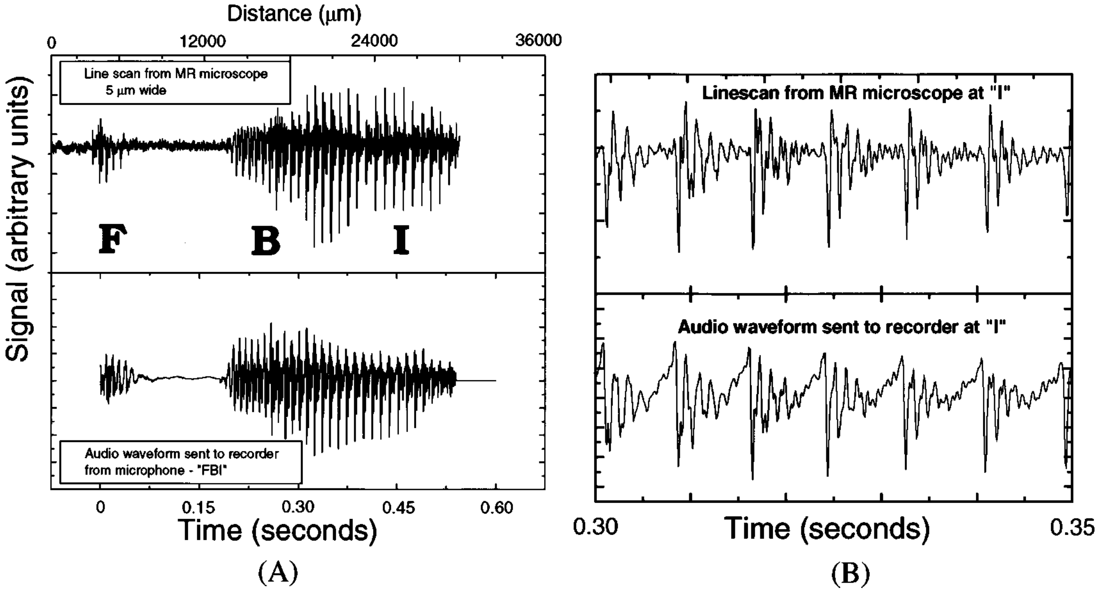

Fig. 7 (a) Upper, a single linescan (5 μm wide) from Fig. 6 down the edge of the inner track of side A; lower, original audio waveform recorded on this track, and (b) expanded view of data from (a) in the region of the letter "I."

the features and artifacts are different for digital media, additional research is necessary to identify events indicative of alteration. However, it is possible to read the low-level binary data directly from these images. This would be useful in a search for deleted (but not erased data) and the recovery of data from damaged samples. In particular, airline flight data recorders are occasionally destroyed in accidents, and it is desired to screen very short (2- to 10-cm-long) pieces of data tape that cannot be read with existing playback systems. The MR microscope works well for these samples.

Figure 9 shows a test sample of magnetic tape recorded with a typical eight-track flight data recorder. Seven of the horizontal tracks can be seen in the image, with a thin slice of the eighth track at the top. The data are written at 2246 bits/in. (11 μm/bit) onto the tape in 768-bit blocks with interrecord gaps between them. These dimensions are well within the resolution and range of the MR microscope and enable the decoding of individual blocks of data.

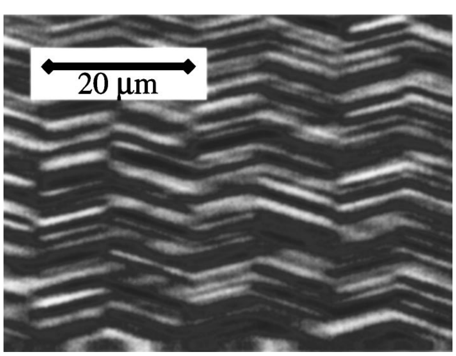

Fig. 8 Image of DAT sample. The tape flow direction goes from the bottom to the top. The chevron pattern is generated by alternating heads of the helical scan system.

The data format is biphase coding. In this type of coding scheme, the recorded signal is clocked from high to low at 2246 bits/in., with the presence of an extra transition indicating a datum 1, otherwise it is a datum 0. We wrote a program that converts each block of image data into binary data. Due to the large amount of data generated in this process and the random nature of the sample, we do not present a decoded block here. Rather, Fig. 10 shows a magnified view of the region between 5.0 and 5.6 mm from Fig. 9. The relevant aspects of the data recovery process are evident in this figure. First, we can see that the data can be read directly from the image (see inset); however, the transitions between the white and black stripes are not sharp. This means that it is necessary to average several linescans to get a representative cross section from a given track. In addition, the recording rate is only nominally constant, resulting in varying distances from bit to bit. This is demonstrated in the third and fourth tracks from the bottom, where two strings of 0's appear side by side. Reading right to left in the direction of the arrow shown, the data tracks start out at the same phase (black to white) at point *a*, and by the time they get to point *b*, the signals are shifted by 90 deg. This demonstrates the necessity for creating an algo-

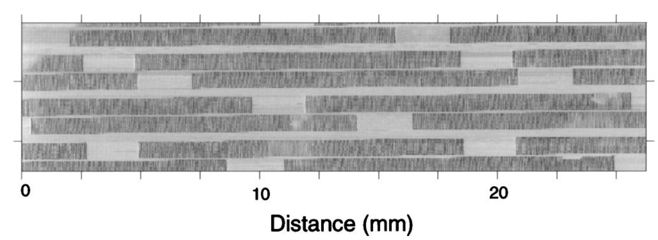

Fig. 9 Image of sample from segment of an eight-track flight data recorder. Complete blocks of data can be read, which may otherwise be not recoverable.

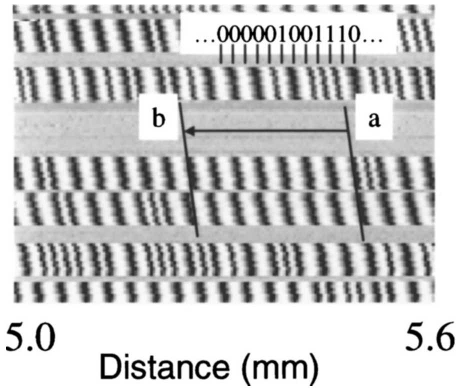

Fig. 10 Magnified view from Fig. 9 showing that the recorded data can be read, either by inspection or automated computer program. The presence of an extra transition in each cycle indicates a 1, and the absence indicates a 0.

rithm that actively compensates for fluctuations in the tape velocity during recording.

6 Discussion

We described and demonstrated the applicability of an MR microscope as a noninvasive method for use in forensics analysis and data recovery. It compares favorably with the ferrofluid technique that is widely used. Other techniques that have been recently developed include imaging using a magneto-optic (MO) garnet film placed in contact with the sample[9] and a scanning superconducting quantum interference device (SQUID) microscopy.[10] The MO garnet film is complementary to the MR microscope because it enables a relatively quick optical inspection of the samples to identify regions of interest. However, data recovery may be complicated in the MO system by the limited field of view and optical defects in the films. Advantages of the MR microscope over the scanning SQUID system are the lower cost, higher resolution, a self-aligned sensor, and no necessity for cryogens.

The most significant advantage of the MR microscope over all of these techniques is the intrinsic scalability of the sensor.[11] It has been demonstrated that large arrays of small sensors can be manufactured to read many tracks simultaneously. A system based on a multielement sensor would be able to scan samples orders of magnitude faster than other techniques. This system, currently under development, will work similarly to a desktop document scanner in principle, and will enable high-resolution, real-time screening of magnetic media evidence. We expect a continuing requirement for improved imaging methods for magnetic analog and digital data tape recordings with an accompanying requirement for high-sensitivity sensors in this area.

Acknowledgments

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