Journal of Imaging Science and Technology® 53(6): 060505–060505-8, 2009.

Technology and Applications of Digital Data Storage on Microfilm

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Abstract. *Digital data storage on microfilm is a highly attractive technology for archiving of digital data. Its estimated storage lifetime of up to 500 years outperforms conventional storage media such as CDs, DVDs, hard drives, or magnetic tapes. Today, migration is widely used as a solution for long-term data storage but unfortunately also requires costly and time-consuming migration steps. Microfilm offers migration-free data storage and also further advantages as the uncomplicated technology of reading devices and hybrid storage of analog and digital data on the same medium. Due to its write once read many character, it is inherently forgery-proof and safe against virus attacks. This article describes the underlying technology of digital data storage on microfilm, including laser recording, error correction codes, and important system parameters. Possible storage capacities are pointed out and potential applications as well as future developments are described. © 2009 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.2009.53.6.060505]

INTRODUCTION

For storing digital data, today's storage media are, e.g., CDs, DVDs, hard drives, or magnetic tapes. All these media have a relatively short lifetime in common (see, e.g., Refs. 1 and 2). Regarding long-term storage, another problem is the availability of corresponding reading devices in the future. A widespread solution for long-term storage of digital data is migration,[3] where the data is copied to a different storage medium or even storage system in certain time intervals. Unfortunately, each migration step is time-consuming and costly.

A well-established medium for storing documents as miniaturized photographs (referred to as *analog images* or *analog data* in the following) is microfilm, which can be found in almost every library and archive. Its main advantage is the estimated storage lifetime of up to several hundred years depending on the material itself and the storage conditions (see, e.g., Ref. 4). There is a variety of standards concerning microfilm: for example, on microfilm vocabulary,[5–12] resolution,[13] production, inspection, and quality assurance,[14] as well as standardized test targets for different applications.[15–18] An overview of several standards and test targets for microfilm and digital imaging as well as a short historical introduction to microfilm can be found in Ref. 19. A detailed introduction to photographic storage of images on microforms is provided in Ref. 20. The generic term *microform* stands for microfilm as well as similar products, such as microfiche or aperture card. Besides classical microform applications based on direct photography, also computer output microfilm (COM) is described. Such COM devices can be used to directly transfer digital images to microforms (see also Refs. 17 and 18 for the definition of the abbreviation COM). Reference 20 further provides an extensive discussion of image scanning and digitization including descriptions of several film scanning technologies.

With the advances in laser film recording for microfilm[21–23] it has been investigated to use this technology also for digital data.[24–29] Laser film recording has formerly successfully been used to expose digital cinema film after the digital postproduction process.[30–32] Besides its lifetime, microfilm offers the possibility to store digital and analog data on the same medium. Moreover, it is a real write once read many (WORM) storage technology that is inherently forgery-proof and safe against virus attacks. Microfilm, as a photographic medium, can be digitized using reading devices that are technologically easy to construct. For low resolutions, even a standard slide scanner is adequate and the magnification of a microscope is sufficient to regard even very small structures on the microfilm. Due to its optical character, the condition of the medium microfilm can always be visually inspected—an important property for long-term data storage that is not feasible for magnetic tapes or hard drives.

This article is about the fundamental technology to store digital data on microfilm and its applications. The underlying technical principles as well as important system parameters are described in detail including error correction codes and laser recording technology. Therefore, this article comprises elements of a technology review and also provides a benchmark of the current state of the art. Special attention is paid to the achievable storage capacity since this is often—not always—one of the most important properties of a storage system. The fundamental dependencies for the storage capacity are discussed, and absolute values are given for the Arche laser [Physical Measurement Techniques (IPM),

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Received Oct. 11, 2008; accepted for publication Jul. 11, 2009; published online Oct. 12, 2009.
1062-3701/2009/53(6)/060505/8/$20.00.

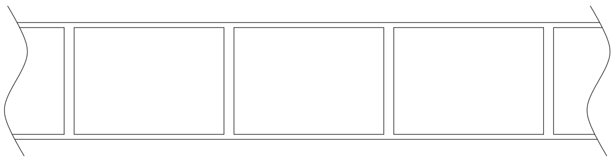

Figure 1. Schematic arrangement of frames on a 35 mm microfilm stripe for the Arche laser recorder.

Freiburg, Germany] recorder as a real system. Finally, possible applications of this emerging technology are pointed out followed by an outlook on further research and development activities.

LASER RECORDING OF FILM MATERIAL

Traditionally, the exposure process of photographic microfilm is achieved by means of a microfilm camera. This kind of setup can, for example, be used to store documents as analog photographic images. Dealing with digital images or data patterns requires techniques to directly transfer the digital information to the film material. This can be achieved by laser film recording techniques. A classical application of digital film recorders is the exposure of cinema film after the digital postproduction process.[30,31] One such system is the ArriLaser based on a robust technology that is reliable and uncomplicated to use.[30] Another application for laser recording is microfilm that is widely used for archiving purposes. A few years ago, the Arche Laser recorder (formerly ArchiveLaser®) was presented to record analog images on color microfilm.[22] An alternative system for laser microfilm recording is described in Ref. 23. Currently under development is the Millenium laser recorder[29] that is especially suited for digital data recording on black-and-white microfilm. It allows smaller data points than the Arche laser recorder and thus smaller grid spaces.

Basically, a laser film recorder is based on a laser beam that is moved over the film material. The laser is modulated according to the data or images to be written on the film, thereby exposing the desired images or data patterns, each consisting of many image pixels or data points, respectively. For color film recording, three separately modulated laser beams (red, green, and blue) are combined to a single beam.

The investigations reported in this article are based on the Arche laser recorder[22] and black-and-white microfilm. Although this recorder was originally developed to write images on color microfilm, it can process black-and-white film as well. It is designed to expose unperforated 35 mm microfilm that is divided into frames. Each frame consists of $10{,}666 \times 15{,}000$ data points or image pixels and has the dimensions 32×45 mm. For this configuration, the *grid space d* (i.e., the distance between the data points or image pixels, respectively) is 3 μm. The schematic arrangement of the frames is depicted in Figure 1. Of course, larger grid spaces as integer multiples of 3 μm can be achieved without changes to the system hardware by omitting the corresponding data points. For example, to realize a grid space of $d=6$ μm, three out of $2 \times 2 = 4$ data points have to be omitted. Note that many of the considerations described within this paper can be applied to other COM recorders as well. Such devices need not necessarily be based on laser technology and may also exhibit different system properties, e.g., regarding grid space, pixel size or shape, and error rates. Also, other microform media, such as microfiche or 16 mm microfilm may be used, depending on the capabilities of the recording device.

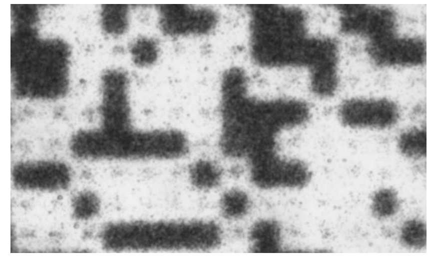

Figure 2. Microscopical image of Dolby® Digital audio data of a cinema film (same magnification as in Figs. 3 and 4).

DATA STORAGE ON FILM MATERIAL

The general idea to record digital information on film is not new. In the 1960s, IBM proposed a system to store digital data on film material.[33] However, photographic film never gained wide acceptance to store digital information in the years after. A few decades later, data storage on film became a widespread solution for storing multichannel cinema sound within the Sony Dynamic Digital Sound® (SDDS®) and the Dolby® Digital systems.[34,35] Therefore, the data is stored in patterns located at the margins of 35 mm cinema film. The microscopical image in Figure 2 shows a part of such a Dolby® Digital data pattern. With the invention of high-resolution laser microfilm recorders, a new interest awakened to store digital information on microfilm with high storage densities.[36,37] During the last few years, the research in this field has become more specific, including first approaches towards a channel model,[24] detailed considerations regarding storage capacities and error correction codes,[25] storage of audio data,[26] and modulation coding.[27] A description on hardware aspects as well as signal processing for data storage on microfilm is provided in our previous work.[28,29] As an alternative approach, the storage of paper and electronic documents as analog images on microfilm or other microform media is discussed by Breslawski.[38]

When storing digital data on film, the information is contained in so-called data points (Figures 3 and 4). The distance between the data points is referred to as the grid space d. When comparing this image to Fig. 2, it is obvious that the data points on the microfilm are much smaller compared to the audio data. The simplest way to store information by means of data points is binary modulation, i.e., the data points are either written or not, thereby representing a logical 1 or 0, respectively. Accordingly, for this method, a single bit can be stored within a data point. By using more than two amplitude levels, the storage capacity can be increased compared to binary modulation. For this amplitude modulation, the number of required amplitude levels N_a can be calculated from the number of bits per data point N_b by

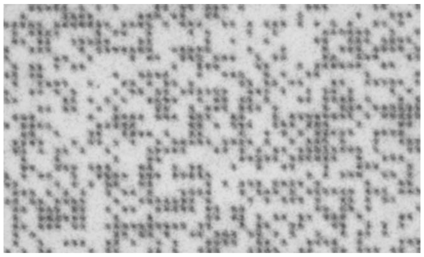

Figure 3. Microscopic image of data points ($d=9$ μm grid space, exposure device: Arche laser recorder).

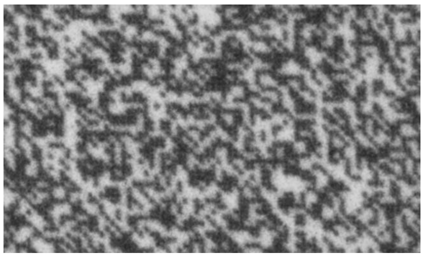

Figure 4. Microscopic image of data points ($d=6$ μm grid space, exposure device: Arche laser recorder).

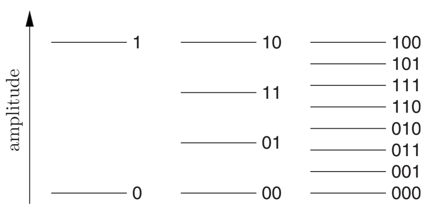

Figure 5. Gray coding for different numbers of amplitude levels N_a.

$N_a=2^{N_b}$. Vice versa, the number of bits N_b can be calculated from the number of amplitude levels by

$$N_b = \log_2(N_a). \tag{1}$$

The characteristic curve of the medium microfilm can only be considered linear within a limited dynamic range.[4,20] An important reason for that is saturation, meaning that beyond a certain level additional exposure does not cause further changes to the film material. Accordingly, the dynamic range has a certain upper limit. Assuming a constant overall dynamic range, a system with a high number of amplitude levels is more susceptible to noise compared to a system with fewer amplitude levels or binary modulation. To improve noise performance for amplitude modulation, e.g., Gray coding[39] can be applied. When using Gray coding, the bit combinations assigned to adjacent amplitude levels differ in only a single bit, as depicted in Figure 5. This is an advantage since in many cases it is reasonable to assume that the most likely error results in a neighboring amplitude level.

ERROR CORRECTION CODING

When storing digital data on microfilm, the read-out of the data points can be affected by dust or scratches (Figures 6 and 7). Furthermore, other effects are possible, e.g., photo-

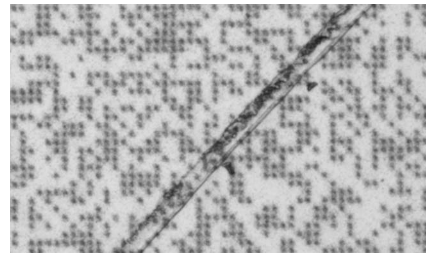

Figure 6. Microscopic image of a scratch on a microfilm (exposure device: Arche laser recorder).

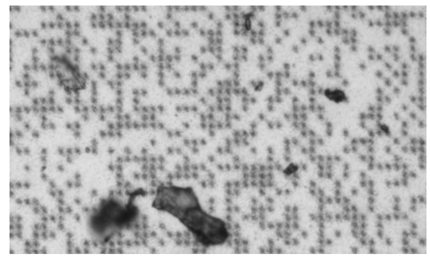

Figure 7. Microscopic image of dust particles on a microfilm (exposure device: Arche laser recorder).

chemical problems or inhomogeneities within the material itself. All these errors can lead to erroneously detected bits of the redigitized data. Accordingly, error correction codes (see, e.g., Ref. 40) are required to ensure a reliable reconstruction of the original data. For data storage systems, forward error correction (FEC) is used. Therefore, an appropriate error correction code is applied in order to add redundancy as additional information to the data before the writing process. This is done by the so-called FEC encoder. After the read-out process, this redundancy is used by the FEC decoder to correct errors. The amount of redundancy is an important factor for the number of errors that can be corrected. Roughly, it can be stated that higher bit error correction capabilities require a larger amount of redundancy. The amount of redundancy is defined by the code rate r as the number of data bits without redundancy (*net bits*) N_n divided by the number of total bits including the redundancy (*gross bits*) N_g:

$$r = \frac{N_n}{N_g}. \tag{2}$$

Besides the code rate r, the choice of a proper code is important to the performance of the forward error correction. As in many other storage systems, the bit errors can occur as bursts in microfilm-based storage systems. The reason for this is that an error source as discussed earlier can cause many bit errors at the same time. So-called Reed-Solomon codes[40,41] are specially suited for these *burst errors*. Alternatively, interleaving[39] can be employed to break these burst errors into several isolated errors.

IMPORTANT SYSTEM PARAMETERS

In order to measure important system parameters, such as a data point's transmission profile or typical gross bit error

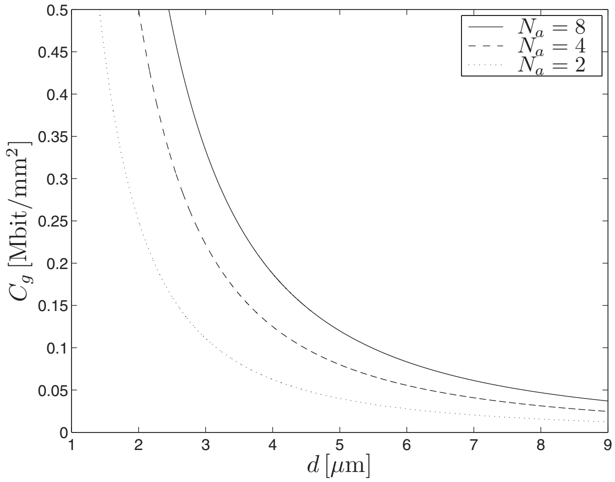

Figure 8. Gross storage capacity C_g depending on the grid space d for N_a=2, N_a=4, and N_a=8 amplitude levels.

rates (BERs), a detailed set of experiments has been carried out. All these experiments are based on test films exposed by the Arche laser recorder with the above-stated technical specifications. For the read-out process, a microscope setup has been specifically adapted for high-resolution imaging of microfilm samples. Besides a high-quality research microscope, this setup includes a high-resolution camera and a motorized precision measuring stage. Both devices are connected to a PC for automated measurements.

One set of test patterns consists of isolated data points at a defined position. Experiments based on these test patterns have shown that the data points' transmission profile can be well-approximated by a Gaussian-shaped function

$$f(x,y,A,\mu_x,\mu_y,\sigma_x,\sigma_y) = A \exp\left\{-\frac{1}{2}\left[\left(\frac{x-\mu_x}{\sigma_x}\right)^2 + \left(\frac{y-\mu_y}{\sigma_y}\right)^2\right]\right\}, \quad (3)$$

with x,y denoting the coordinates and A being an amplitude value. The variables μ_x,μ_y define the center and σ_x,σ_y the shape of the data points (Ref. 25). Regarding the parameters σ_x and σ_y, a specific set of test patterns turned out to exhibit a rotational-symmetric profile with $\sigma_x = \sigma_y \approx 2.21$ μm.

Due to the finite extension of the data points, interference is caused, meaning the overlap of data points. Figure 8 shows simulated data points for the grid spaces $d=\{3,6,9\}$ μm. It is obvious that for $d=9$ μm, the data points are spaced quite apart from each other, whereas for $d=6$ μm, the data points are spaced much closer but are still well distinguishable. However, for a grid space $d=3$ μm, the data points are so close that they form a continuum and cannot be distinguished from each other. For reducing interference, either the data points must be made smaller (by decreasing σ_x,σ_y) or the grid space d has to be increased.

For the measurement of typical gross bit error rates, random patterns have been exposed. By comparing the original bit pattern with the bit pattern read from the microfilm, the number of errors could be obtained. Afterwards, the bit error rate was calculated as the number of errors divided by the total number of exposed bits. As typical values, gross bit error rates around 1% have been observed for $d=6$ μm and binary modulation. This gross bit error rate can in turn be used to choose an appropriate error correction code, as we will see in the following.

SELECTION OF ERROR CORRECTION CODES

The measured gross bit error rate of about 1% is now our starting point to draw conclusions concerning possible code rates r. We achieve this by simply assuming binary phase shift keying (BPSK) modulation which is widely used in wireless communication systems. For BPSK over additive white Gaussian noise (AWGN) channels, the performance of FEC codes is very well documented in literature (see, e.g., Refs. 41–43). The theoretical bit error rate p_e over an AWGN channel for BPSK is given by

$$p_e = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_s}{N_0}}\right), \quad (4)$$

with the channel signal-to-noise ratio (SNR) E_s/N_0 and the complementary error function

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty \exp(-t^2)dt. \quad (5)$$

E_s denotes the energy per symbol and $N_0/2$ is the noise power spectral density[39]. We justify the use of AWGN/BPSK results from literature by two distinct properties of the microfilm channel and modulation:

(1) The microfilm channel is appropriately interleaved and can thus be assumed to be memoryless—as AWGN.
(2) Using $N_a=2$ amplitude levels we have a binary modulation—as it is BPSK.

The selection of a proper error correction code can now be achieved in two steps: first, the measured gross BER of 1% (i.e., the BER *without* error correction) is transformed into the corresponding E_s/N_0 value using Eq. (4). The second step is to select a suitable FEC code with a code rate r that satisfies a certain net BER. This can be done on the basis of the E_s/N_0 value obtained through Eq. (4). Note that in literature channel code performance is usually reported as a function of E_b/N_0, with E_b being the energy per net bit (data bit). This allows us to compare different codes at equal transmission power. However, we have to deal with a system-given p_e and thus E_s/N_0, therefore we simply require to identify codes which achieve a certain net BER (i.e., the BER *with* error correction).

We encounter the practical problem that error correction codes are usually only evaluated for net bit error rates down to values around $10^{-4}-10^{-6}$. The reason for this is the computational complexity of the corresponding simulations.

Table I. Redundancy estimations for RCPC-Codes described in Ref. 42 (net BER $=10^{-5}$).

p_e (%)	E_s/N_0 (dB)	Largest possible r	Redundancy (%)	Margin (dB)
0.1	6.8	8/9 (≈0.89)	≈11	0.8
0.5	5.2	8/12 (≈0.67)	≈33	1.9
1.0	4.3	8/12 (≈0.67)	≈33	1.0
3.0	2.5	8/16 (=0.5)	≈50	0.6
5.0	1.3	8/24 (≈0.33)	≈67	1.3

However, for a microfilm-based data storage system, residual bit error rates below 10^{-12} are desirable. Accordingly, for the estimation of the code rate r, a target net BER of 10^{-5} (*quality of service*) is evaluated with a certain margin for E_s/N_0 that in practice will lead to the desired lower bit error rates of 10^{-12}. This is a reasonable approach since the curve progression is generally quite steep for low net bit error rates.

In addition, the Shannon limit[40] can be calculated, as a theoretical limit for the largest possible code rate r (i.e., the minimum amount of redundancy) depending on the gross BER. Please note that the AWGN/BPSK analogy only provides a rough estimation for the code rate r.

As an example, the RCPC codes (rate punctured convolutional codes) suggested by Haugenauer[42] are further regarded. Using Eq. (4), our measured gross bit error rate of 1% for $N_a=2$ and $d=6$ μm corresponds to a signal-to-noise ratio $E_s/N_0=4.3$ dB. According to Hagenauer,[42] an RCPC with code rate $r=8/12$ exists that satisfies a net bit error rate of 10^{-5} still with 1.0 dB margin. The result of this estimation is given in Table I also for further gross bit error rates 0.1%, 0.5%, 1.0% (the above-mentioned case), 3.0%, and 5.0%, which correspond to and may be measured with larger or smaller grid spaces, respectively. The corresponding maximum possible code rates r clearly show that the measured gross bit error rate p_e has a significant influence on the redundancy which has to be introduced by an FEC code.

The codes mentioned in Ref. 42 are investigated for *soft decision*, meaning that the FEC decoder obtains additional information on the reliability of the received gross bits (as opposed to *hard decision*). All advanced error correction codes usually comprise *soft decision* (see, e.g., Refs. 40, 41, and 43). Furthermore, even a higher code rate r compared to the values given in Table I can be achieved by using other codes. As an example, the RS(31,28,4) Reed-Solomon Block Turbo Code with code rate $r=0.81$ is investigated in Ref. 41. For this code, an $E_s/N_0=3.5$ dB according to the definition Eq. (4) would be sufficient to assure a gross BER of 10^{-5} (with 0.8 dB margin).

It becomes evident that a suitable code must be carefully chosen in order to fulfill a systems' error performance and quality of service. Based on the above-mentioned considerations, we assume for the storage capacity estimations that a practical code with $r=0.75$ exists which is suitable for a gross bit error rate of 1%. As a comparison, the Shannon limit for this gross BER is approximately $r\approx 0.95$.

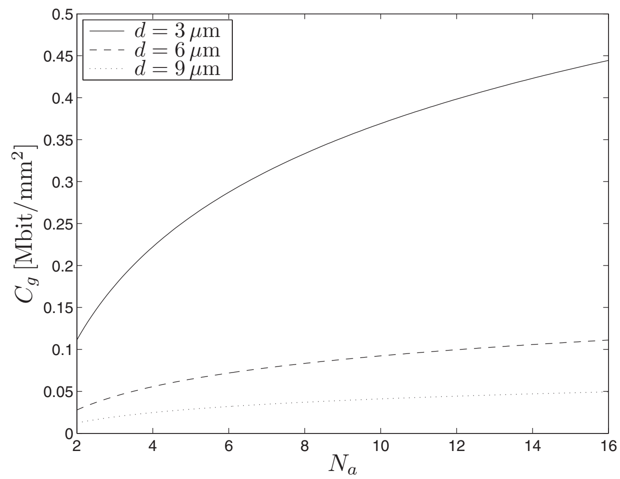

Figure 9. Gross storage capacity C_g depending on the number of amplitude levels N_a for grid spaces $d=3$ μm, $d=6$ μm, and $d=9$ μm.

STORAGE CAPACITY

The storage capacity is one of the most important parameters of a data storage system. The gross storage capacity C_g, i.e., the storage capacity without considering error correction, file system, synchronization etc., is logarithmically dependent on the number of amplitude levels N_a according to

$$C_g \propto \log_2 N_a \tag{6}$$

and inversely quadratically dependent on the grid space d:

$$C_g \propto \frac{1}{d^2}. \tag{7}$$

Its absolute value (in bits per area) can be calculated as

$$C_g = \frac{1}{d^2}\log_2(N_a) \quad [\text{bit}/\mu\text{m}^2]. \tag{8}$$

The resulting capacities for grid spaces $d=\{3,6,9\}$ μm and $N_a=\{2,4,8\}$ amplitude levels are presented in Figures 9 and 10. It is obvious that—compared to the number of amplitude levels N_a—the grid space d has a much higher impact on the gross storage capacity C_g. This is due to the quadratic dependency described by Eq. (7) and the weaker logarithmic dependency described by Eq. (6). Regarding Fig. 10, the storage capacity drastically increases for small grid spaces d for all amplitude levels. In contrast, the diagram in Fig. 9 shows that a higher number of amplitude levels only moderately influences the gross storage capacity C_g.

The truly available capacity per microfilm area is referred to as the net storage capacity C_n,

$$C_n = C_g r\eta = \frac{r\eta}{d^2}\log_2(N_a) \quad [\text{bit}/\mu\text{m}^2], \tag{9}$$

defined as the product of the gross storage capacity C_g, the code rate r, and a factor η that takes into account further overhead, e.g., due to synchronization and file system $(0<\eta\leq 1)$.

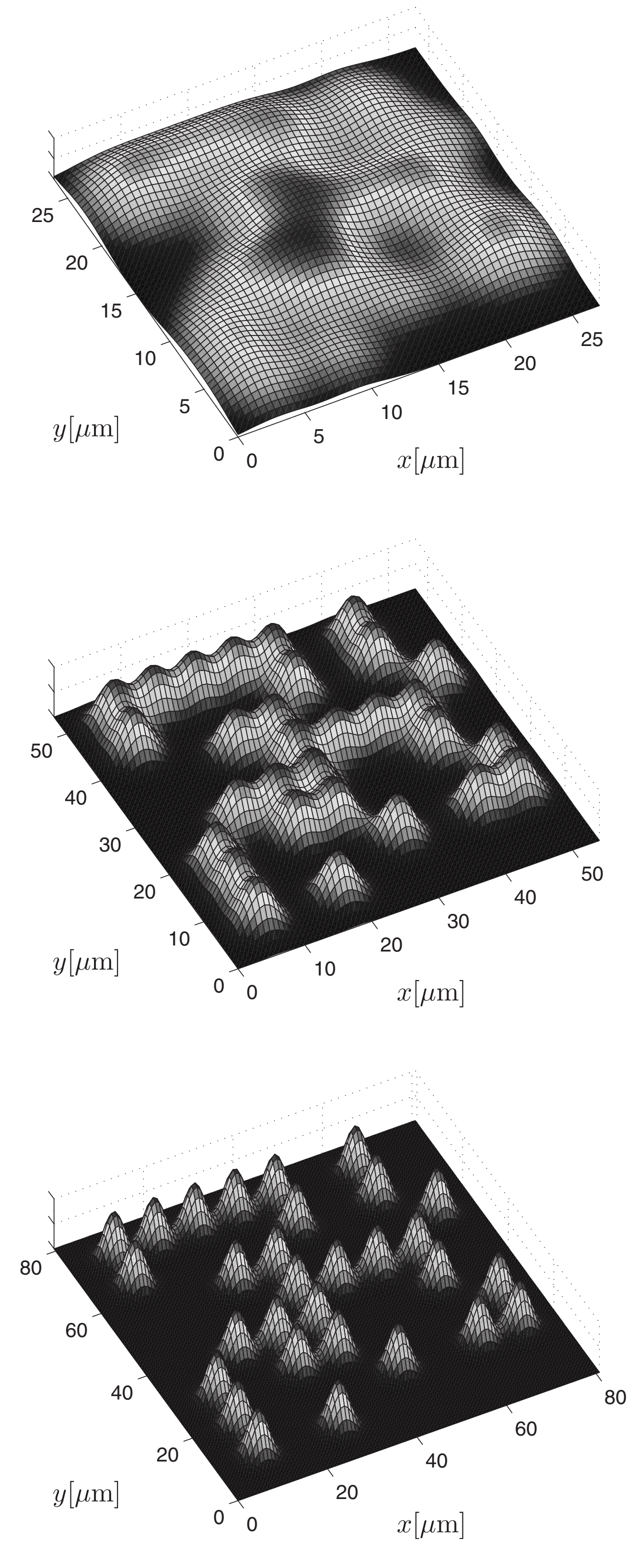

Figure 10. Exposure simulations with 3 μm (top), 6 μm (middle), and 9 μm (bottom) grid space without noise for binary modulation assuming linear system behavior. Each simulation is based on the same bit pattern (Ref. 25).

Realistic gross and net storage capacities can be calculated using the parameters of the Arche laser recorder as mentioned before. Table II shows the gross storage capacity C_g of one meter microfilm for grid spaces $d=\{3,6,9\}$ μm and $N_a=\{2,4,8\}$ amplitude levels. Again, the strong influence of the grid space d compared to the weaker influence of the number of amplitude levels N_a is visible. The diagram in Fig. 11 shows possible net storage capacities C_n, with overhead due to file system, synchronization etc., being neglected ($\eta=1$). The bars mark the range between an easy-to-find code with $r=0.75$ and the Shannon limit $r=0.95$ as figured out in the last section assuming 1% gross BER at all grid spaces d. Each of the three bars in the diagram corresponds to a different grid space $d=\{3,6,9\}$ μm. Note that achieving $p_e=1\%$ at $d=3$ μm will be a challenging task, while for $d=6$ μm our system already achieves $p_e=1\%$. It is obvious that the modification of the code rate r allows a variation in the net storage capacity within the bars, whereas the selection of a different grid space allows a *jump* between the bars. Furthermore, it can be observed that the possible range is much bigger for smaller grid spaces d.

Table II. Gross storage capacity C_g of 1 m microfilm for different numbers of amplitude levels and grid spaces.

	$N_a=2$ (MByte)	$N_a=4$ (MByte)	$N_a=8$ (MByte)
$d=3$ μm	416.7	833.3	1250
$d=6$ μm	104.2	208.3	312.5
$d=9$ μm	46.3	92.6	138.9

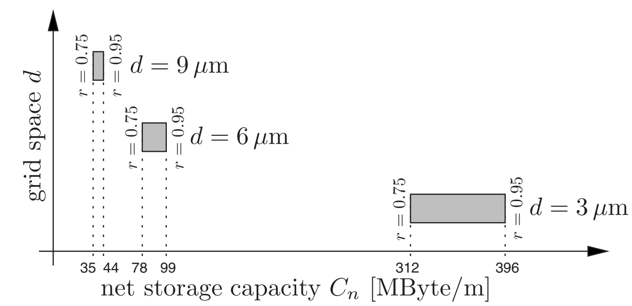

Figure 11. Possible net storage capacities C_n for the Arche laser recorder assuming $\eta=1$. The bars mark the range from a realistic code with $r=0.75$ to the Shannon limit $r=0.95$ assuming 1% gross BER at all grid spaces d (figure according to Ref. 25).

Clearly, a joint optimization of the three parameters code rate r, number of amplitude levels N_a, and grid space d is necessary in order to achieve an optimum storage capacity. Due to its strong influence, the grid space d deserves first priority within this optimization.

APPLICATIONS

Microfilm-based long-term data storage has a wide range of applications. Basically, there is no limitation which type of data can be stored on the film. However, besides the physical aspects of data storage, the data format deserves special attention. Regarding the extensive lifetime of the medium microfilm, it has to be made sure that the data stored on the film can also be accessed and interpreted in the future. When thinking of the many and fast-changing formats in the multimedia sector, it is not guaranteed that each of these data formats can be understood in a few hundred years. Therefore, it makes sense to use (at least) well-standardized formats such as PDF/A[44,45] that are especially suited for long-term storage applications.

Furthermore, microfilm offers far more possibilities by using hybrid recording of digital data and analog images. This allows the storage of documents, pictures, or even audio in a digital format on the film along with analog images of the same documents, pictures, or acoustical waveforms, respectively. This can be interesting for high-security storage of important documents. Even if all digital mechanisms to error correction etc. fail, there is still an analog version of the digital data. This guarantees an extra level of data security. Furthermore, hybrid recording offers the possibility to store a detailed description of the coding parameters or how to read and interpret the data on the microfilm as analog documents or images.

Possible customers of microfilm-based long-term storage solutions are libraries, archives, governments, the healthcare sector, banks and insurances, as well as any other sector where data has to be stored reliably for a long time horizon. It can even be interesting for the private sector to protect important data in certain intervals, e.g., private images, documents, or family registers. In contrast to migration-based long-term storage, microfilm requires no time-consuming and expensive migration steps. Regarding the availability of reading devices, microfilm can be read with relatively simple optical instruments. All equipment required is a high-resolution scanner and even a microscope can be used to read at least small parts of a microfilm stripe. As microfilm is a WORM medium, it is inherently forgery-proof and safe against virus attacks.

CONCLUSIONS

In this article we discussed microfilm as a migration-free solution for long-term data storage. Because of its long lifetime of up to 500 years, costly and time-consuming migration steps are avoided. Further advantages of this technology are the hybrid storage of analog and digital data on the same medium and the forgery-proof WORM-type of technology. Another significant factor is that reading devices are technologically easy to construct.

Regarding storage capacity, we have described and analyzed the main dependencies. It has been pointed out that the grid space d is a very important parameter towards an increased storage capacity. For the Arche laser recorder, possible absolute values for the net and gross storage capacity have been presented.

Current focus of our research activities are innovative signal processing techniques to allow smaller grid spaces even in the presence of strong interference. Error correction codes are investigated in conjunction with an improved channel model. Also, the new Millenium laser recorder is under construction to allow smaller grid spaces than the Arche laser recorder. Current aim of research is a gross storage capacity of 250 MByte/m.

ACKNOWLEDGMENTS

The research described in this article has been funded by the German Federal Ministry of Economics and Technology (BMWi) within the project MILLENIUM. The laser exposure technology was developed at Fraunhofer Institute for Physical Measurement Techniques (IPM) in Freiburg, Germany. We thank our colleagues at IPM for many exposed film samples. Furthermore, the authors would like to thank their colleague Volker Märgner for his valued support in image processing issues.

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