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# Thermally Balanced Writing for High-Speed Compact Disc Recordable (CD-R) Recording

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A thermally balanced write strategy has been developed for high-speed recording of CD-recordable (CD-R). It is adopted in the recent multi-speed CD-R standard as the media testing condition. The write strategy accounts for the effects of thermal interference and heat accumulation during the recording process. Detailed thermal calculations of the resulting pit shapes and sizes support the approach. CD-R recording speeds of up to 40X are demonstrated using this Thermally Balanced Write Strategy. [DOI: 10.1143/JJAP.41.1735]

KEYWORDS: optical recording system, CD-R, high-speed recording, dye recording, thermal interference, thermal balancing, write strategy, multi-speed CD-R standard, speed race

## 1. Introduction

Soon after the introduction of CD-recordable (CD-R),[1,2] the tendency towards higher recording speeds started to develop. In the last three years, this speed race has had an enormous impact on the optical recording industry. The “X-factor” for CD-R recording, indicating the speed factor with respect to the default speed of CD-audio, has become the major parameter indicating optical drive performance. Today, optical drives with 24X recording speed are on the market. Along with faster drives and discs on the market, the CD-R standard has evolved in the speed race as well. An upgrade of the Orange Book, the Multi-Speed CD-R standard,[3] was released for speeds up to 16X in January 2001. The release for speeds up to 32X is planned in October 2001.

A major challenge in achieving these high recording speeds lies in the definition of the write strategy, both for use in the actual recorder and for defining a media test condition for the CD-R standard. The challenge for recording at higher linear velocities lies in the increased in-track thermal interference between pits and the heat accumulation during recording of long pits. To improve recording at high speeds, thermal balancing is proposed to diminish thermal interference to a great extent. In this paper, we report on the write performance of such thermally balanced write strategies and on thermal calculations supporting the concept of thermal balancing.

## 2. Thermal Interference and Heat Accumulation

The recording process for CD-R discs is based on irreversible deformation and decomposition of a thin recording layer by heating the dye. The deformed area is called a pit and has lower reflection. Between these pits, unmodified areas of higher reflection remain, referred to as “lands” Variation of the land and pit lengths in a predetermined sequence enables the storage of binary data. The quality of bit-detection during readout of data is mainly determined by the uncertainty in the position of the pit edges. This uncertainty in pit position is reflected in timing uncertainty, better known as timing jitter.

At low recording speeds, the accuracy of the placement of the pit edges depends mainly on the steepness of the spatial temperature gradient in the recording layer (dye). During recording of data at low speeds, the time between consecutive pits is long enough to allow for sufficient local cool down in the data track.

For recording at speeds higher than 4X, the time between two consecutive write pulses is reduced and accordingly the cool down is less efficient. Heat diffusion due to the large amount of dissipated recording power causes heating of neighboring pits in the track, disturbing their shape and position. Therefore, the writing behavior is strongly influenced by the thermal properties of the disc. Consequently, the positioning of pit-edges is no longer determined by the laser pulse alone, but also by the in-track thermal crosstalk in the disc due to the writing of adjacent pits.[4,5]

There are two directions of in-track thermal crosstalk as depicted in Fig. 1. When a pit is written, the heat injected in the disc to write the previous pit diffuses towards the position where the current pit has to start. This residual amount of heat is referred to as “pre-heat” and results in pit expansion at the leading edge. The amount of pre-heat encountered depends mainly on the length of the previous unwritten area in the track, the land. Therefore, pits are expanded with a random magnitude since the length of the previous land is random.

The second type of thermal crosstalk is caused by writing of the next pit and is called post-heat. When the next pit is written, the injected heat diffuses back towards the previous pit and disturbs its cool-down behavior. Both pre- and post-heat depend on the land lengths surrounding the pits and alter the pit edges, giving rise to a systematic increase of the jitter of the recorded marks.

In addition to the influence of the surrounding pits, there are heat accumulation effects within pits to be considered. For long marks, heat is accumulated which leads to an unintentional expansion of the pit for longer run lengths. At higher recording speeds, the difference in heat accumulation

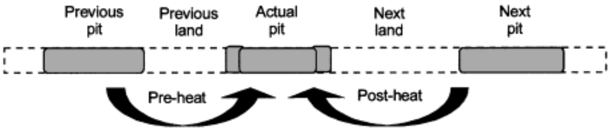

Fig. 1. In-track thermal interference. Pre-heat and post-heat influence the leading and trailing edges of marks, respectively.

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*Corresponding author. E-mail address: Benno.Tieke@philips.com for short and long pits is increasing because the duration of the write pulse decreases whereas the thermal response time of the disc is unchanged.

## 3. Thermally Balanced Write Strategy

Figure 2 shows the preferred write strategy of the initial CD-R standard, which is suitable for the speed range from 1X to 4X.[1)] It starts with an increased power level "$\Delta P$" during a 1.5 clock cycle. A pulse shortening of $\theta = 0.5$ to $\theta = 1.0$ is used to compensate for the spot size. Whereas it is well suited for low-speed recording, this write strategy does not perform well at high speeds because it does not account for thermal interference and heat accumulation.

Therefore, we have developed the concept of a thermally balanced write strategy (TBWS) for speeds of 4X and higher. The basic idea is to compensate in a natural way for the systematic thermal influences during the recording process, i.e. such a write strategy has to account for thermal interference and heat accumulation. A simplified form of a TBWS has been included in the multi-speed CD-R standard[2)] as the write strategy for media testing (see Fig. 3).

As described in §2, thermal interference between consecutive pits is more severe for short intermediate lands. Of course, the most critical run length for the recording performance is I3. The pre-heat is accounted for by a thermal compensation delay $\tau$ of the leading edge of the write pulse when the previous land is short (a 3 T land). By introducing this delay $\tau$, the leading edges of all pits have identical nominal position, which minimizes the pit jitter.

Post-heat is different from pre-heat because post-heat does not directly disturb the pit creation but the cool-down of recorded pits. However, the thermal properties of the disc as well the length and time scales involved are identical to those for pre-heat. Therefore, the pre-heat compensation $\tau$ simultaneously decreases the post-heat effect on the previous pit.

The second element of the TBWS is the so-called write equalization to account for the heat accumulation in the longer marks. Also in this case, the I3 (pit) is the most critical run length. Due to heat accumulation, the longer marks are wider than the shortest mark. An I3 pit written with the same write power as the longer marks is therefore systematically too small. The result is insufficient modulation and length of the I3 pit. One could attempt to compensate for this smaller width by making the I3 pit slightly longer. However, it is much better to eliminate the problem exactly where it arises. Thus, a power boost $\Delta P$ for only the I3 pit ensures an equal mark width for the I3 and longer pits. Another advantage of changing the power level for individual pit lengths is that for all pit lengths the peak temperature and the temperature distribution at the end of a pit are identical. Therefore, there are no second-order effects of heat interference from one pit to the next. In this case, compensating for land-pit combinations is indeed sufficient.

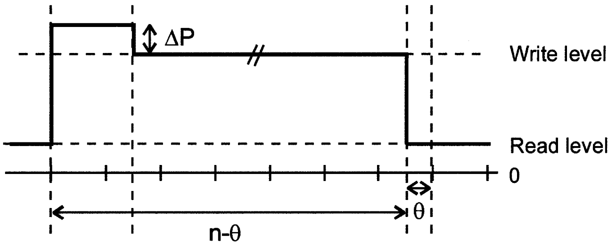

Fig. 2. Write strategy suitable for CD-R recording from 1X up to 4X.[2)]

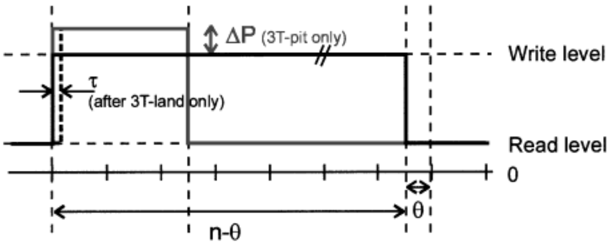

Fig. 3. Thermally balanced write strategy (TBWS).[3)] The delay $\tau$ at the leading edge of the pulse (after I3 land only) compensates for the pre-heat. The power boost $\Delta P$ for the 3 T pit only compensates for heat accumulation in long pits.

Finally, the TBWS also has a general pulse shortening $\theta$ as in the conventional write strategy to compensate for the spot size. For higher recording speeds, $\theta$ can also be used to decrease the overall write power by choosing longer pulses. This option can be beneficial in some cases to prevent problems in the disc due to the high absolute peak powers at high recording speeds.

For the write strategy described in this section, thermal balancing is restricted to the shortest run length (I3). This basic form of TBWS has been included in the Multi-Speed CD-R standard because it is very simple to implement and at the same time provides a representative measure of media performance. The I3-only correction is in most cases sufficient because thermal interference decreases rapidly with increasing distance between pits. Of course, the performance can be improved by applying the same principle to other run-lengths.

## 4. Thermal Simulations: Pit Formation

A three-dimensional finite-difference model was used to calculate the temperature distribution in a planar multi-layer write-once disc due to laser-light absorption.[6)] The heat source was calculated from the numerical aperture of the objective lens, the wavelength of the laser light, and the optical properties (index of refraction and absorption coefficient) of the different layers in the disc. Heat diffusion due to a moving heat source was then calculated based on the thermal properties (thermal conductivity and heat capacity) of the different recording layers and of the substrate.

Pit formation was modelled as a threshold phenomenon. When a single transition temperature (250°C in this case) is exceeded, a pit is formed. A pit of length nT is typically simulated with a pulse length of nT. The simulated pit shapes and sizes (widths of about 800 to 900 nm) are in good agreement with actual pit sizes in CD-R. The fact that such realistic pit sizes are obtained with nominal write powers of 30 mW at 32X (similar to experimental values) illustrates that the model as well as the input parameters represent the recording situation quite well.

The exact transition temperature is not of great importance because mainly relative differences in pit shape and size are considered at the moment. We are currently working on a better understanding of the pit formation process and the results of that study will be implemented in the pit formation model in the future. We note however, that the current model already yields reliable results and is capable of predicting trends.

The influence of pre-heat on the following pit is illustrated in Fig. 4. The gray area defined by the closed squares shows an I3 pit written after an I11 space. Such a pit can be seen as a nominal I3 pit. If instead of an I11 space the pit is preceded by an I3 space, the pre-heat present in the disc leads to an extension of the I3 (shown by the open squares in the figure). It is apparent from Fig. 4 that the pre-heat leads only to a shift of the leading edge of the pit; the trailing edge is in both cases identical.

In order to give a better impression of the absolute size of the shift of the leading edge, we have zoomed in on this edge in Fig. 5. The calculated shift is 28 nm, as indicated. Since the channel bit length is 277 nm, this position shift corresponds to a time shift of T/10, where T is the channel clock. The calculated time shift is in good agreement with the optimum value for the pre-heat compensation parameter in the TBWS.

The pit formation model was also used to study differences in pit size between short and long pits when similar write powers are used. The predicted pit shapes are shown in Fig. 6 for an I3 pit (solid squares) and an I11 pit (solid triangles). It can be observed that the I11 pit is wider than the I3 pit, clearly showing the effect of heat accumulation within the pit. In read out, the smaller width not only yields a smaller I3 modulation but also, more importantly, a shorter I3 length, which in turn results in an increased land jitter. By increasing the I3 write power by 16% to 35 mW, an I3 pit is obtained which has about the same width as the I11 (in fact, it is even a bit too wide). This behavior is in good agreement with the optimum value for the I3 power boost in the TBWS, which typically amounts to about 10%.

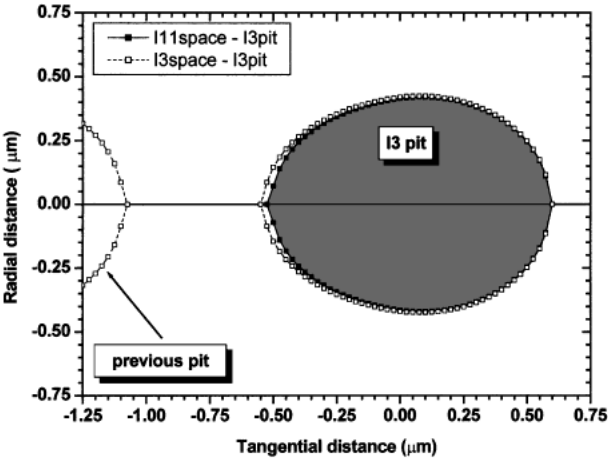

Fig. 4. Thermal calculation of I3 pit. Solid squares give the mark edge of an I3 pit following an I11 land; open squares show the mark edge of an I3 pit following an I3 land. The leading edge is clearly shifted. (For details on the calculations, see text.).

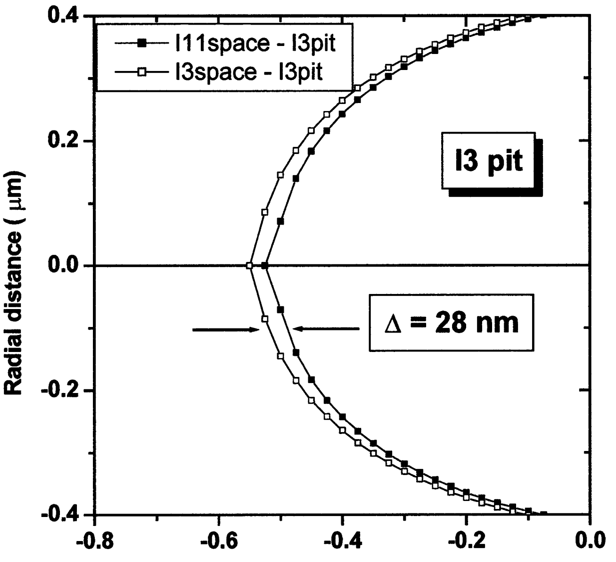

Fig. 5. Enlarged view of the I3 leading edge from Fig. 4. The leading edge of the I3 pit after the I3 land is shifted clearly to the left. The shift is 28 nm corresponding to a time shift of 0.1 T.

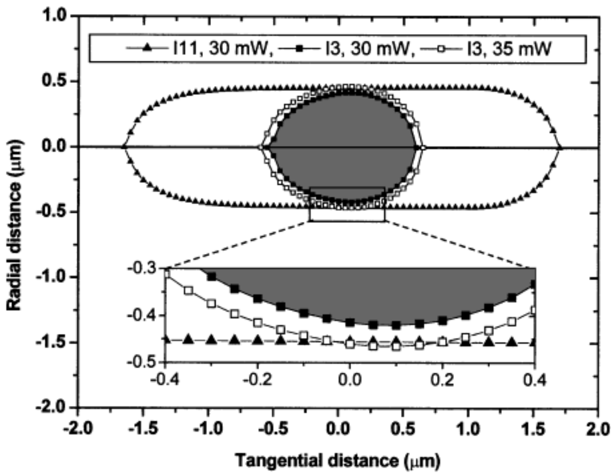

Fig. 6. Simulation of an I3 pit (solid squares) compared to an I11 pit (solid triangles) with identical write powers. The I3 pit clearly has a smaller width. The difference in width can be compensated by an increased write power for the I3 pit (open squares). The effect on mark width can be best observed in the enlarged view of the lower mark edge.

## 5. Experimental Results

To study the effectiveness of the TBWS, we have constructed an experimental recording setup with an optical light path according to the Multi-Speed CD-R standard. The setup enables recording at very high rotational speeds (> 150 Hz) and thus linear velocities (> 48 m/s). A thermally balanced write strategy was successfully applied to many discs in the recording speed range from 4X up to 40X. An example of writing at a recording speed of 16X on a cyanine disc is presented in Fig. 7. Shown are data-to-data jitters of pits and lands as a function of write power. Whereas it is not possible to obtain acceptable jitter performance below 35 ns using a conventional write strategy, the recording is well within orange book (OB) specifications for the TBWS. The bottom jitter is low (25 ns) and the power margin is large for recording within OB specifications.

We have verified that the TBWS as defined in the multi-speed CD-R standard is also applicable to speeds higher than 16X. We have recorded discs of all principal dye types (cyanine, phthalo-cyanine, and azo) at 32X within specifications (i.e., data-data jitter below 35 ns) using the TBWS of Fig. 3. As an example, the results for three discs (one of each dye type) are shown in Fig. 8. It is remarkable that this large variety of discs with different dye types can be recorded with

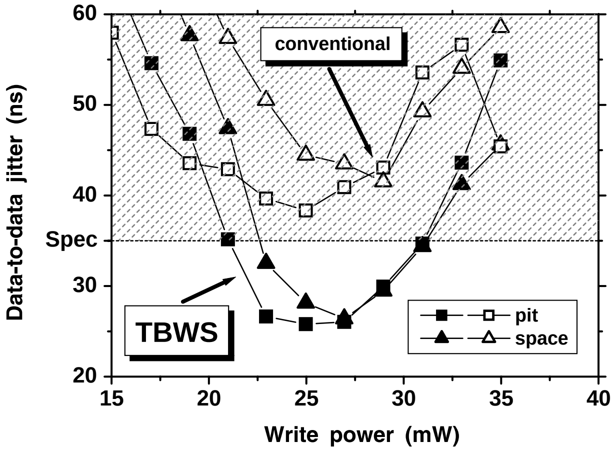

Fig. 7. Data-to-data jitter as function of write power: experimental comparison at 16X recording speed between the conventional write strategy and the thermally balanced write strategy (TBWS) on a cyanine disc. With the TBWS, recording within the Orange Book specification of 35 ns data-to-data jitter is clearly possible.

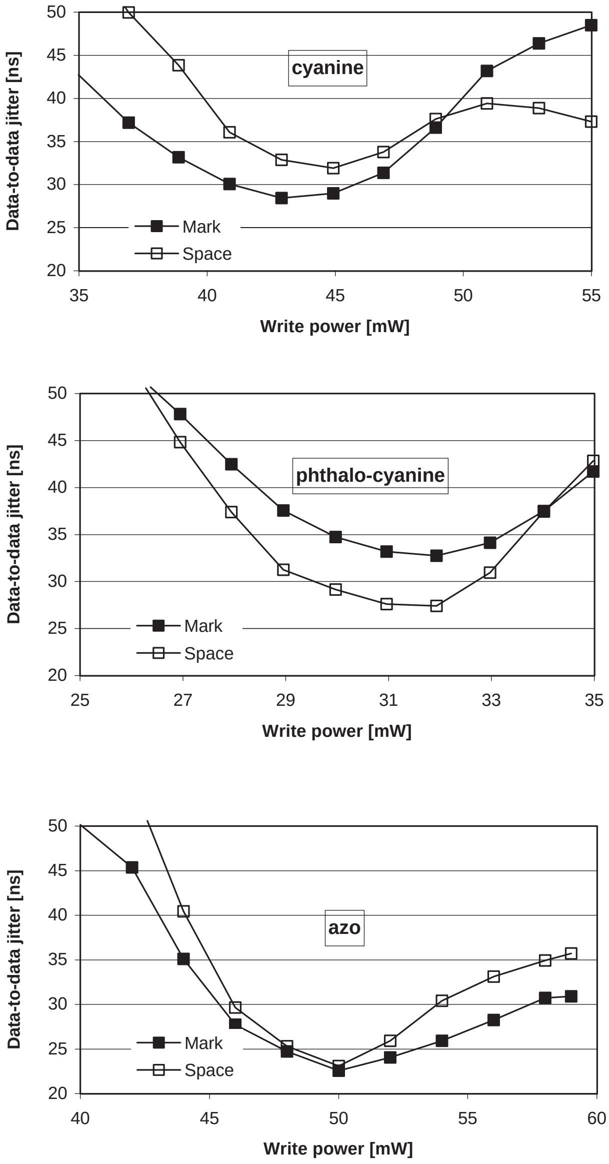

Fig. 8. Data-to-data jitter as a function of write power at 32X using the TBWS of Fig. 3. Results for one disc per dye type are shown; cyanine (top), phthalo-cyanine (middle) and azo (bottom). Recording within OB specification of 35 ns is possible for all three discs.

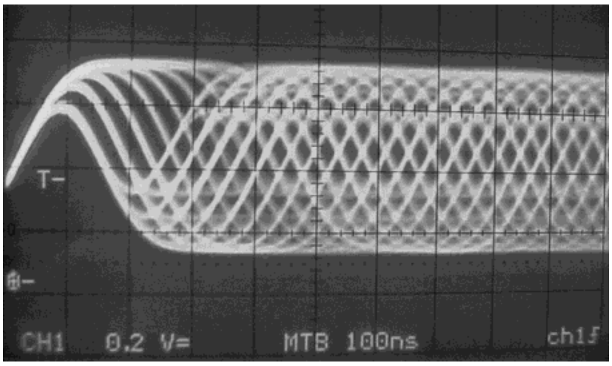

Fig. 9. Eye pattern of random EFM data recorded at 40X on a cyanine disc using the thermally balanced write strategy. The corresponding data-to-data jitter was 28 ns.

a write strategy containing only two specific thermal parameters, the thermal interference compensation $\tau$ and the write equalization $\Delta P$, in addition to the general pulse length parameter $\theta$. This conceptual simplicity makes reliable standardization and media certification possible.

Recently, we have even been able to perform recordings at 40X with jitters below 35 ns on our recording platform using the TBWS. An example of an eye pattern recorded at 40X on a cyanine disc is shown in Fig. 9. The jitter of the recorded data was 28 ns. With the demonstration of recording at 40X, we are very close to achieving the final goal of writing data on an optical disc at the same maximum speed as is possible for reading data.

## 6. Conclusions

Conventional write strategies used for low-speed CD-R fail for high recording speeds due to in-track thermal interference between and within written pits. To enable recording at high speeds, a thermally balanced write strategy for CD-R was developed. It consists of thermal interference compensation and write equalization. Although very simple, this thermally balanced write strategy enables recording at 32X on a large variety of CD-Rs. Furthermore, we have demonstrated successful recording at 40X using the TBWS. The write strategy was adopted as a mandatory write strategy for media testing in the multi-speed CD-R standard for recording speeds up to 32X.

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