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Feasibility Study of Implementing Simple Dual-bit Detection in Dual-Layer Bit-Patterned Magnetic Recording Systems

Natthakan Rueangnetr[1], Simon John Greaves[2], and Chanon Warisarn[1]*

[1]*School of Integrated Innovative Technology (SIITec), King Mongkut's Institute of Technology Ladkrabang (KMITL), No. 1 Chalongkrung rd. Ladkrabang, Bangkok 10520, Thailand*
[2]*Research Institute of Electrical Communication (RIEC), 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan*

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Dual-layer bit-patterned magnetic recording (DL-BPMR) systems, which combine bit-patterned magnetic recording (BPMR) and multi-layer magnetic recording technologies, are expected to increase the areal density (AD) of data storage up to 10 Terabits per square inch. However, to achieve this goal, several challenges must be overcome, including low response signals from the lower layer and interlayer interference. Therefore, this work proposes a signal processing technique to reduce the number of erroneous bits at the receiver. A simple dual-bit detection (SD-BD) method is proposed. Simulation results comparing the performance of a single-layer BPMR system with that of a DL-BPMR system using the SD-BD signal processing technique show that the latter can effectively reduce the bit error rate. The results indicate that the SD-BD technique has the potential to improve the read accuracy of the DL-BPMR system and is an essential step towards the future development of data recording technologies with higher AD.

Keywords : Dual-layer bit-patterned magnetic recording (DL-BPMR), Interlayer interference (ILI), Simple dual-bit detection (SD-BD) technique

1. Introduction

The latest advance in magnetic recording technology for hard disk drives is known as perpendicular magnetic recording (PMR). PMR is approaching the super-paramagnetic limit, a phenomenon that leads to a loss of thermal stability in the recording media. As a result, this instability can cause the magnetic grains—responsible for recording—to change their magnetization more easily. Current magnetic recording technologies face challenges in increasing the areal density (AD) of data storage beyond 1 terabits per square inch (Tb/in^2). To address this limitation, it is essential to develop new magnetic recording technologies. One promising approach that has garnered interest among researchers worldwide is bit-patterned magnetic recording (BPMR). This innovative technology has the potential to achieve AD exceeding 4 Tb/in^2 [1, 2], where the user bits are stored on magnetic bit islands surrounded by non-magnetic material. This structure allows for greater storage capacities compared to existing PMR technology.

To enhance the AD of BPMR technology, it is crucial to shorten the distance between bit islands and reduce the spacing between tracks. Consequently, the readback signal is greatly affected by inter-symbol interference (ISI) and inter-track interference (ITI). This situation increases the likelihood of erroneous data detection, ultimately reducing the overall performance of the recording system. To address this issue, BPMR technology has been integrated with multi-layer magnetic recording (MLMR) systems, which we refer to as dual-layer bit-patterned magnetic recording (DL-BPMR) technology. DL-BPMR can double the areal density (AD) and is expected to provide up to 10 Tb/in^2 [3-8] by utilizing the principle of stacking multiple layers on a single platter. DL-BPMR can significantly enhance data storage capacity by using all three dimensions, as illustrated in Fig. 1. The design of DL-BPMR is similar to that of single-layer BPMR (SL-BPMR). Still, it has two recording layers,

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*Corresponding author: Tel: +66 8-6997-1001
Fax: +66 2-329-8263, e-mail: chanon.wa@kmitl.ac.th

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each consisting of arrays of magnetic islands that act as separate storage units. Therefore, in theory, dual-layer BPMR can double the areal density compared to a single-layer recording.

Despite advancements in DL-BPMR technology, challenges remain. A significant issue is the lower-layer signal response, as illustrated in Fig. 2, which can complicate data retrieval due to the extremely low signal level. Separating the signals sourced from the upper and lower layers of a composite readback signal poses a significant challenge in DL-BPMR systems, as both layers are read simultaneously. Additionally, inter-layer interference (ILI) is a unique issue in DL-BPMR systems, where the magnetic fields from each layer interfere with one another during the reading process. This interference presents one of the key problems to address, and minimizing the impact of ILI is crucial for maintaining the highest AD.

To mitigate the impact of ILI, numerous studies have suggested the development of advanced signal processing systems. For instance, research referenced in studies [4-8] has focused on enhancing the signal processing capabilities of magnetic recording systems using dual-layer media. This research specifically aimed to improve channel detection techniques, both in one-dimensional (1-D) and two-dimensional (2-D) contexts, known as 1-D/2-D partial response maximum likelihood (PRML) [9, 10]. Findings indicate that the improved detection techniques can perform effectively in magnetic recording systems featuring dual layers without necessitating modifications to the thicknesses of the recording layers. To further enhance the efficiency of detection, this study proposes a signal processing scheme employing a simple dual-bit detection (SD-BD) technique. This technique is based on a data recording channel model illustrated in Fig. 3. The approach leverages the differences in reader response between two layers, which exhibit varying signal levels, to create an effective detection system. It operates on the principle of determining whether the bit recorded on each layer should be classified as a ‘+1’ or ‘−1’. The results indicate that the SD-BD technique can enhance the detection rate of DL-BPMR systems and perform better than SL-BPMR systems at the same AD of 4 Tb/in², considering media noise.

2. DL-BPMR Channel Model

This work aimed to study a DL-BPMR system in which the bit islands in each layer were arranged in an orthogonal grid pattern, as illustrated in Fig. 1. The centers of the bit islands in each layer were aligned, with an AD of 2 Tb/in^2. The parameters T_x and T_z represent the bit spacing and the distance between tracks, respectively, and were set at 18 nanometers (nm), while the diameter of the bit islands (D) was 10 nm. The processes for reading and writing data are described through the DL-BPMR channels depicted in Fig. 3. The user bit or input data sequence $u_k \in \{\pm 1\}$ was divided into the odd-track data sequence $u_{k,0}$ and the even-track data sequence $u_{k,1}$,

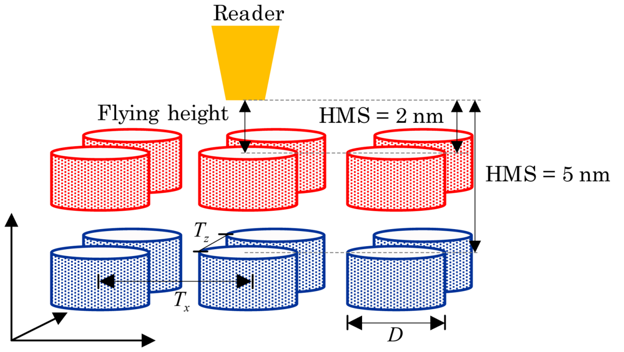

Fig. 1. (Color online) Cross-sectional view of the dual-layer media structure and head-media spacing (HMS) for both layers, showing the distance between the media layers and the reader.

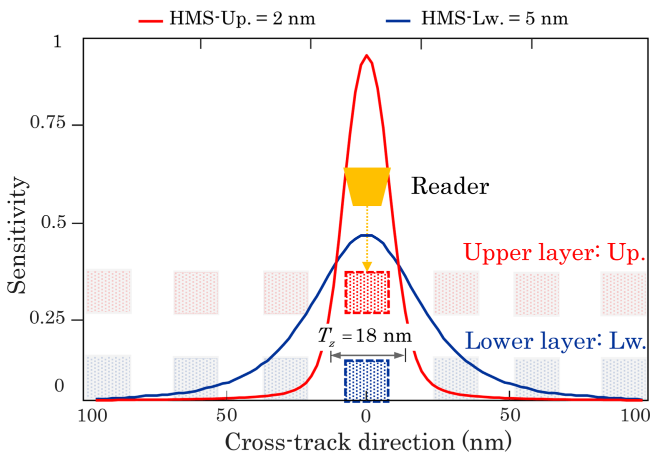

Fig. 2. (Color online) Reader sensitivity functions of the upper and lower layers cover the bit islands.

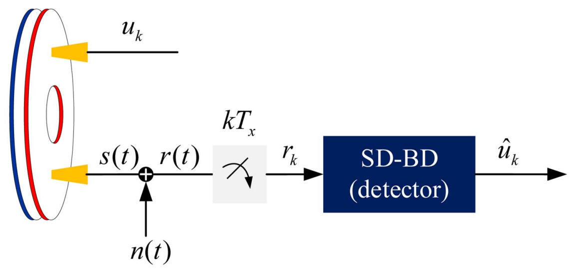

Fig. 3. (Color online) Channel model of DL-BPMR systems using the SD-BD technique.

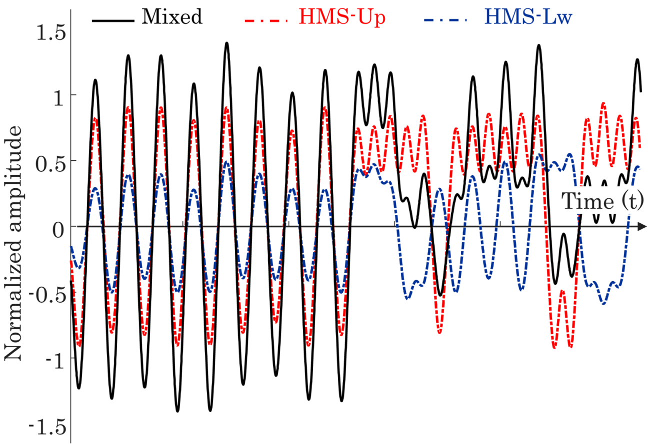

Fig. 4. (Color online) Examples of noise−free readback signals. The blue−dashed and red−dashed lines represent the readback signals from the upper and lower layers, respectively. In contrast, the black solid line represents the composite (mixed) readback signal generated by simultaneous reading of both layers.

which were recorded on the upper and lower layers, respectively. To read the data, the reader is positioned at the center of the target track. An example of a readback signal is shown in Fig. 4. In this study, the distance between the reader and the media, termed head-to-media spacing (HMS), was 2 nm for the upper layer and 5 nm for the lower layer.

The readback signal $r(x,y)$ is a function of the ordered pair (x,y), obtained by a 2-D convolution of the magnetic properties of each island in the media, denoted as $m(x,y) \in \{\pm 1\}$ and the reader sensitivity function, $h(x,y)$ [11], The readback signal can be mathematically expressed as

$$r(x,y) = \iint m(\xi,\eta)\, h(x-\xi, y-\eta)\, d\xi d\eta . \quad (1)$$

Since the reader is always positioned at the center of the target track, the readback signals from the upper and lower layers can be represented as $r_{up}(t)$ and $r_{lw}(t)$, respectively. The composite readback signal, therefore, is the sum of the readback signals from both layers, which can be mathematically expressed as:

$$r(t) = r_{up}(t) + r_{lw}(t) + w(t), \quad (2)$$

where $w(t)$ represents additive white Gaussian noise (AWGN), the composite readback signal $r(t)$ is then sampled to obtain the discrete-time readback signal r_k, where $r_k = r(kT_x)$. This discrete-time readback can be utilized to design a simple dual-bit detection method for enhancing the performance of DL-BPMR systems, which will be discussed in the next section.

3. Simple Dual−Bit Detection (SD-BD) Technique

Consider that the readback signal depends on the recorded bit pattern, as illustrated in Fig. 5. The peak amplitude of the readback signal varies based on the four possible configurations of the recorded bits. When both layers have the same recorded bits, such as (−1, −1) or (+1, +1), the readback signal reaches its highest peak amplitude in either the positive or negative direction. Conversely, when the recorded bits in the layers differ, such as (−1, +1) or (+1, −1), the signals from the bits in both layers are not identical. This difference produces distinct peak amplitudes in the readback signal, leading to unique peak patterns based on the specific combinations of recorded bits. Thus, the peak amplitude of the readback signal is intricately linked to the arrangement of recorded bits in the medium, as demonstrated in Fig. 5.

Additionally, we also consider the distribution of readback signal amplitudes, as shown in Fig. 6, which can be categorized into four distinct groups. All four possible patterns of recorded bits were collected, and their peak amplitudes were observed. Here, we minimize the impact of electronic noise by fixing the SNR at 18 dB, allowing us to focus on the core elements without distraction. Additionally, the media noise is defined as 10% to evaluate the threshold value when the recording system encounters media noise. Fig. 6(a) indicates that the readback signals from each layer can be separated when it was examined without media noise. Consequently, threshold detection can be employed to simultaneously classify the user bits from both layers by detecting dual

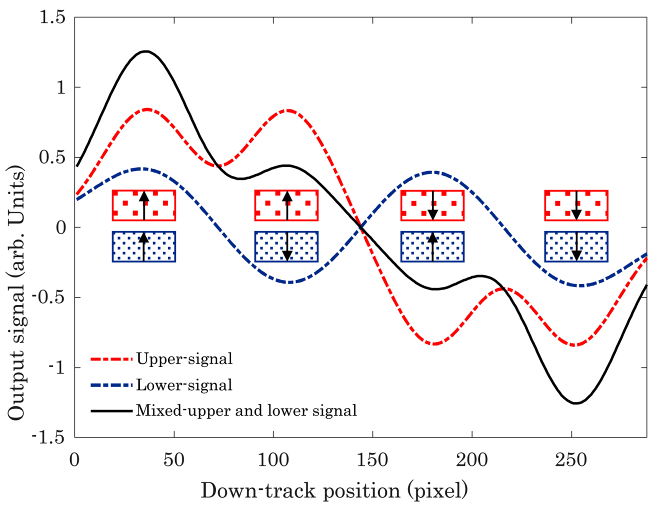

Fig. 5. (Color online) Examples of noise−free readback signals for all four possible recorded bit patterns, obtained by combining the readback signals from the lower and upper layers.

bits at the same time. For example, if the readback signal has a peak amplitude of around −0.50, it implies that the corresponding recorded bits should be '−1' in the upper layer and '+1' in the lower layer. On the other hand, when the obtained peak amplitude is around +1.25, the estimated user bits should be '+1' for both layers. This approach not only enhances the simple detection efficiency but also minimizes errors arising from interference between the layers. In the case of considering media noise, as illustrated in Fig. 6(b), overlapping areas appear between each data group, indicating the impact of media noise on the recording system. However, we can effectively separate each data group using a straightforward threshold detection method. Furthermore, this study highlights that the obtained amplitude of the readback signal is a crucial factor for distinguishing the recorded bits in both layers, which will be highly beneficial for developing detection techniques in future MLMR systems.

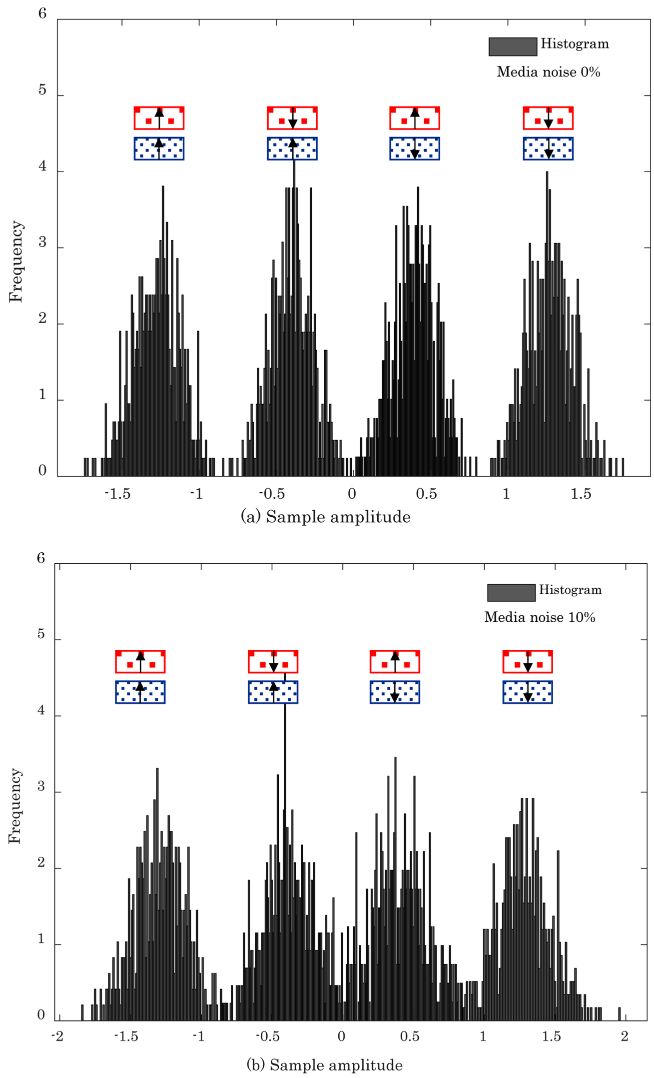

Fig. 6. (Color online) Distributions of peak amplitude values in the histogram form for the four possible bit patterns recorded on the upper and lower layers at SNR = 18 dB (a) without media noise effect and (b) with 10% media noise effect.

4. Simulation Results

In evaluating the performance of various recording systems, we compared the proposed system with a conventional magnetic recording system. Specifically, we evaluated an SL-BPMR system that employed a decision threshold and 1D PRML detection [9, 10, 12]. For this comparison, the AD was set to 4 Tb/in^2. We measured the performance of each system in terms of the bit error rate (BER) versus the signal-to-noise ratio (SNR).

Fig. 7 illustrates the process of determining the optimal threshold for separating data groups or clustering the amplitudes of the readback signals. This threshold helps decide the recorded bit status for all recorded patterns across different layers. The graph presents the relationship between the threshold (α), and the minimum BER at an SNR of 18 dB. The red line indicates how the BER varied with the threshold value, with the lowest BER occurring when $\alpha = 0.85$. This value corresponds to the lowest BER achievable, suggesting that using this threshold can significantly reduce decision errors, thereby enhancing the system's accuracy in data decoding and decision-making. Consequently, the SD-BD technique utilizes this threshold value to determine the estimated user bits.

For example, as shown in Fig. 6, when the sample

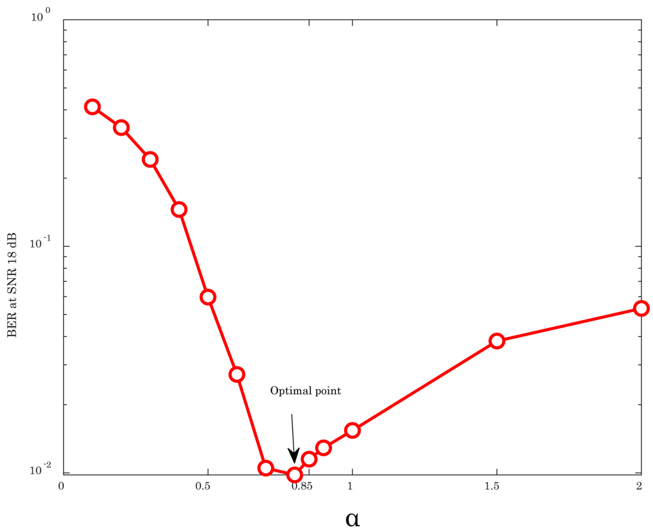

Fig. 7. (Color online) The optimal point used as the threshold for bit detection based on minimizing the BER at an SNR of 18 dB.

amplitudes are greater than 0.85 or less than −0.85, the detected bits of both the upper and lower layers should be '+1' or '−1,' respectively. For sample values between 0 and 0.85, the detected bits for the upper and lower layers should be '+1' and '−1,' respectively. Conversely, for sample values between 0 and −0.85, the detected bits for the upper and lower layers should be '−1' and '+1,' respectively. To formalize the threshold-based classification method used in the SD-BD technique, the following rule is applied to determine the estimated user bits in the upper and lower layers based on the sampled readback signal,

$$(\hat{u}_{k,0}, \hat{u}_{k,1}) = \begin{cases} (+1,+1), & \text{if } r_k > \alpha \\ (+1,-1), & \text{if } 0 < r_k \le \alpha \\ (-1,+1), & \text{if } -\alpha \le r_k < 0 \\ (-1,-1), & \text{if } r_k < -\alpha \end{cases}, \tag{3}$$

where α = 0.85 is the empirically selected threshold that minimizes the BER under typical noise conditions.

Fig. 8 illustrates the relationship between BER and SNR for SL-BPMR and DL-BPMR systems, assuming no track misregistration. The media noise was set to 0%, 5%, or 10%. The SL-BPMR system was evaluated using both threshold detection (TD) and the 1-D PRML technique. A 1-D minimum mean squared error (MMSE) equalizer [10] and 1-D Viterbi detector were employed to process the readback signal. Here, the DL-BPMR system was only evaluated with the SD-BD technique. The "SL-TD" and "SL-1D PRML" curves represent single-layer systems

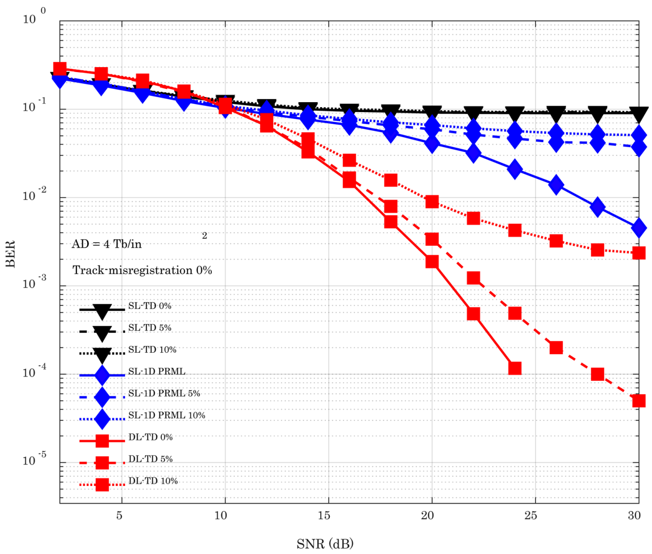

Fig. 8. (Color online) BER performance comparison of various recording systems at an AD of 4 Tb/in² with 0%, 5% and 10% media noise.

using the threshold detector and 1-D PRML technique, respectively, while the "DL-TD" curves represent the dual-layer system using the SD-BD technique.

The results indicate that the SL-TD could not achieve satisfactory BER performance due to the significant impact of ISI and ITI. These effects can be alleviated by employing the SL-1D PRML technique, which demonstrated improved BER performance compared to a traditional threshold detector. However, media noise negatively affected the performance of the SL-1D PRML system. On the other hand, the DL-BPMR technique yielded better BER performance, achieving lower error rates than the SL-BPMR and other standard threshold detection techniques, especially under high SNR conditions. Media noise also influenced the DL-BPMR systems; however, they still delivered better BER performance than the SL-1D PRML system.

5. Conclusion

This study aimed to enhance the areal density (AD) of magnetic data storage by examining various issues within the dual-layer bit-patterned magnetic recording (DL-BPMR) system, such as low signal response from the lower layer and interference between layers. We developed signal processing techniques to improve bit detection using a simple dual-bit detection (SD-BD) approach. The evaluation results demonstrate that DL-BPMR systems employing the SD-BD technique can achieve lower bit error rates compared to single-layer bit-patterned magnetic recording systems that use threshold detectors or partial response maximum likelihood techniques, at an AD of 4 Tb/in^2. This indicates that the proposed system effectively reduces data detection errors, providing valuable insights for the future development of magnetic recording technologies.

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