

# Double-Track PRML Detection for Two-Track Reading with a Wide-Track Reader in Shingled Magnetic Recording Systems

Anawin Khametong<sup>1</sup>, Simon John Greaves<sup>2</sup>, and Chanon Warisarn<sup>1\*</sup>

<sup>1</sup>*School of Integrated Innovative Technology (SIITec), King Mongkut's Institute of Technology Ladkrabang (KMITL),  
No. 1 Chalalongkrong Rd. Ladkrabang, Bangkok 10520, Thailand*

<sup>2</sup>*Research Institute of Electrical Communication (RIEC), 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan*

(Received 27 April 2025, Received in final form 21 August 2025, Accepted 21 August 2025)

The utilization of two-track simultaneous reading is proposed to avoid the requirement for a narrow track reader in shingled magnetic recording systems, where partial response maximum likelihood detection and recursive decoding by oversampling techniques are employed for decoding. To develop effective decoding techniques when reading two tracks with a wide-track reader, we propose utilizing a pre-coding scheme along with a modified Viterbi detector. A pre-coder and an oversampling scheme are first adopted, where the sampling points are located at the centers of the front and rear halves of the recorded bits. The Trellis diagram of the conventional Viterbi algorithm is then modified according to all possible transitions of the readback signal obtained from two-track simultaneous reading. The proposed technique can simultaneously detect two data tracks. Simulation results indicate that at an areal density of 2 Tb/in<sup>2</sup>, the proposed system offers improved performance regarding the bit-error rate.

**Keywords :** Wide-track reader, shingled magnetic recording systems, modified Viterbi algorithm, Trellis diagram, partial response maximum likelihood detection

## 1. Introduction

To effectively manage the vast amounts of information in today's digital age, storage devices such as hard disk drives must be developed to realize higher areal density (AD). Various recording technologies have been proposed, e.g., two-dimensional magnetic recording [1], heat-assisted magnetic recording [2], and microwave-assisted magnetic recording [3], which are expected to overcome the current perpendicular recording technology's superparamagnetic limitation, leading to higher AD. These technologies can employ shingled writing, where data tracks are written sequentially by a corner writer [4], to obtain narrower tracks than conventional writing. However, substantial intertrack interference (ITI) continues to pose a significant challenge in these recording systems. The two-dimensional (2D) partial response maximum likelihood (PRML)

approach has been effectively used to address the ITI effect. For example, researchers proposed the use of a 2D equalizer along with a one-dimensional (1D) target design to mitigate the ITI effect in media with and without a soft underlayer [5] for bit-patterned magnetic recording. However, the performance of the 1D detector remains poor because it struggles to handle the intensity of the ITI. In response to this limitation, joint-track equalization and detection techniques have been introduced [6]. With this new technique, both the 2D equalizer and 2D target can be developed, leading to a significant improvement in performance compared to the 1D detector. Currently, shingled magnetic recording (SMR) systems can provide very high AD. The track width is becoming narrower, resulting in a higher ITI. To address the extremely severe ITI, therefore, a two-track reading system with a wide-track reader was developed for shingled recording [7], as shown in Fig. 1. This technique can simultaneously decode the recorded data in two neighboring tracks with one wide-track reader through both oversampling detection and PRML techniques.

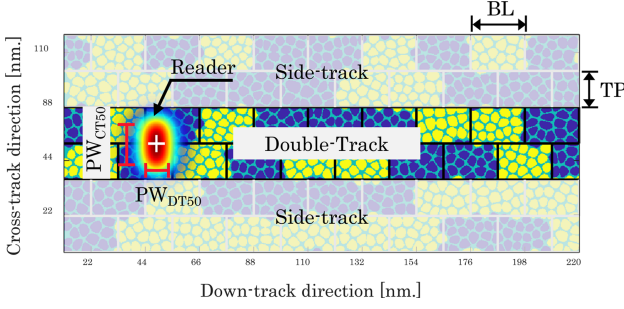
Oversampling detection can easily determine the magnetization that is sensed by a wide-track reader whose

©The Korean Magnetism Society. All rights reserved.

\*Corresponding author: Tel: +66 8-6997-1001

Fax: +66 2-329-8263, e-mail: chanon.wa@kmitl.ac.th

This paper was presented at the ICAUMS 2025, Okinawa, Japan, April 21-24, 2025.



**Fig. 1.** (Color online) The structure of shingled magnetic recording shows the recorded magnetization distribution in a two-track recording scheme, where the reader is positioned at the center of the two desired tracks, with sensitivity reader dimensions corresponding to  $PW_{CT50} = 22$  nm and  $PW_{DT50} = 13.50$  nm.

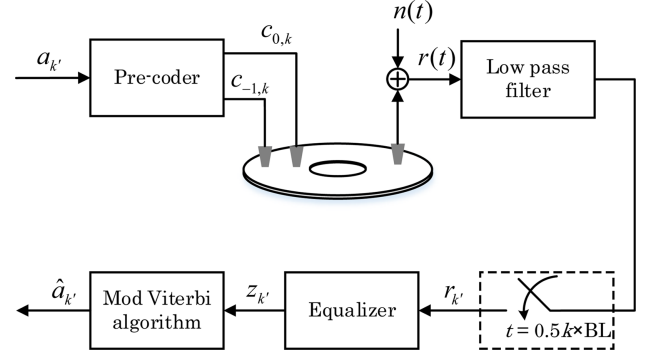
width covers two neighboring tracks. Samples, or signal amplitudes, can be obtained at sampling points that are located at the centers of the front and rear halves of the recorded bits, when the amplitude of the readback tracks should be ‘+1’ or ‘−1,’ respectively. On the other hand, when the amplitude is 0, it cannot be determined which of the two tracks has a ‘+1’ bit and which has a ‘−1’ bit. However, this problem can be addressed using a pre-coding scheme. Double-track PRML is another proposed technique [7]. By sampling at the bit transition of each track, the sampling amplitudes are distributed across five distinct levels. Therefore, the partial-response-2 (PR-2) channel can easily be applied for operating on these samples.

To improve the effectiveness of the decoding technique in two-track reading with a wide-track reader, this paper presents the use of a pre-coding scheme along with a modified Viterbi detector. The samples collected through oversampling at the centers of the front and rear halves of the recorded magnetization, like the approach used in the aforementioned oversampling detection, can be processed using the proposed modified Viterbi detector. In this method, the Trellis diagram is designed to account for all possible transitions of the recorded magnetization. The results show that our proposed system can significantly improve bit error rate (BER) performance compared to conventional single-track reading, oversampling detection, and previous double-track PRML systems at the same AD.

The remainder of this paper is organized as follows: Section 2 describes a channel model. Section 3 outlines the proposed systems. Simulation results and conclusions are presented in Sections 4 and 5, respectively.

## 2. Double-Track PRML Channel Model

Fig. 2 illustrates the channel model of a shingled

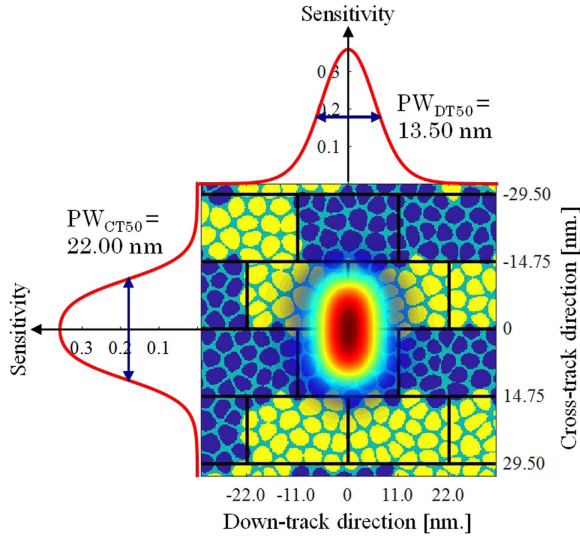


**Fig. 2.** Channel model of a shingled magnetic recording system with the proposed modified Viterbi detector.

magnetic recording system with a proposed modified Viterbi detector. The user bits,  $a_k \in \{\pm 1\}$ , are sent to the pre-coder to rearrange the recorded bits according to their respective tracks, where the recorded bits are generated according to Table 1. For example, if the user bit is ‘+1,’ the  $k$ -th recorded bit of the upper track,  $c_{0,k}$ , must be defined as ‘−1’ if the  $k$ -th recorded bit of the lower track,  $c_{-1,k}$ , was ‘−1’. Similarly, the  $k$ -th recorded bit of the upper track should be ‘+1’ if the  $k$ -th recorded bit of the lower track was ‘+1’. In contrast, if the user bit is ‘−1,’ the  $k$ -th recorded bit of the upper track,  $c_{0,k}$ , must be defined as ‘−1’ if the  $k$ -th recorded bit of the lower track,  $c_{-1,k}$ , was ‘+1’. While the  $k$ -th recorded bit of the upper track should be ‘+1’ if the  $k$ -th recorded bit of the lower track was ‘−1.’ Using this pre-coding, when we sample the readback signal at the centers of the front and rear halves of the recorded magnetization, we should get a sample amplitude of around +2 or −2 for a ‘+1’ user bit, and 0 for a ‘−1’ user bit. To read the data, the reader is positioned centrally between the two tracks considered, as shown in Fig. 1. The double-track readback signal can be obtained from a two-dimensional (2D) convolution of the reader sensitivity function and the magnetization of the granular media, as shown in Fig. 3. In this study, we have employed the reader sensitivity function based on the M. Yamashita et al. model [8], which provides a closed-form expression for accurately evaluating the reader sensitivity

**Table 1.** Relationship between the user bits and the recorded bits as determined by the pre-coding process.

| User bits<br>$a_{k'}$ | Recorded bits         |                        | Peak<br>amplitude |
|-----------------------|-----------------------|------------------------|-------------------|
|                       | Upper track $c_{0,k}$ | Lower track $c_{-1,k}$ |                   |
| +1                    | −1                    | −1                     | −2                |
| +1                    | +1                    | +1                     | +2                |
| −1                    | −1                    | +1                     | 0                 |
| −1                    | +1                    | −1                     | 0                 |



**Fig. 3.** (Color online) An example of the reader sensitivity function covered on granular media in the down-track and cross-track directions, where  $PW_{CT50}$  and  $PW_{DT50}$  are equal to 22 nm and 13.5 nm in the cross-track and down-track directions, respectively.

in practical applications. This sensitivity function enables us to create more realistic readback signal modeling. The reader sensitivity function can be expressed as:

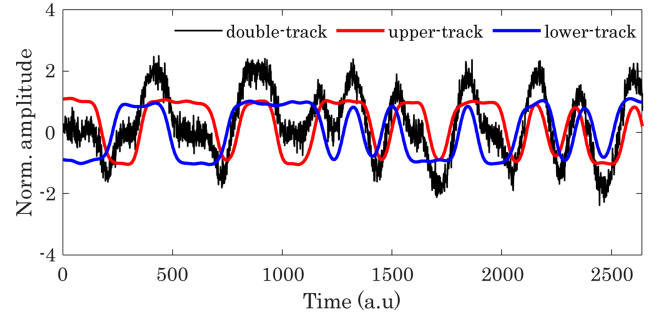
$$h(x, y) = \alpha_0 \left\{ \tanh(\alpha_1 x + \alpha_2) - \tanh(\alpha_1 x + \alpha_2) \right\} \times \tanh(\alpha_3 y + \alpha_4) - \tanh(\alpha_3 y + \alpha_4), \quad (1)$$

where  $x$  and  $y$  are the width of the reader sensitivity function, and  $\alpha_k$  is the fitting parameter, which can be expressed as:

$$\alpha_k = \left\langle \left[ H \ G \ T \ U \ h_m \ t_m \ t_s \ 1 \right]^T, \mathbf{w}_k \right\rangle. \quad (2)$$

The geometric parameters are defined as follows:  $H$  is the width between side shields,  $G$  is the shield gap,  $T$  is the width of the magnetoresistive (MR) element,  $U$  is the thickness of the MR element,  $h_m$  is the magnetic spacing,  $t_m$  is the thickness of the recording layer, and  $t_s$  is the substrate thickness,  $\mathbf{w}_k$  is the weights vector.  $|\cdot|$  is the absolute operator,  $\langle \cdot \rangle$  is the inner product, and  $[\cdot]^T$  is the transpose operator. For our simulations, we set the geometric parameters as:  $H = 26$  nm,  $G = 15$  nm,  $T = 13$  nm,  $U = 2$  nm,  $h_m = 4$  nm,  $t_m = 10$  nm, and  $t_s = 1$  nm. These parameters are utilized for both single-track and double-track detection methods throughout this study.

The reader response in the cross-track direction is wider than in the down-track direction. These widths can be referred to as the pulse width at half maximum of the reader sensitivity function in the cross-track direction,



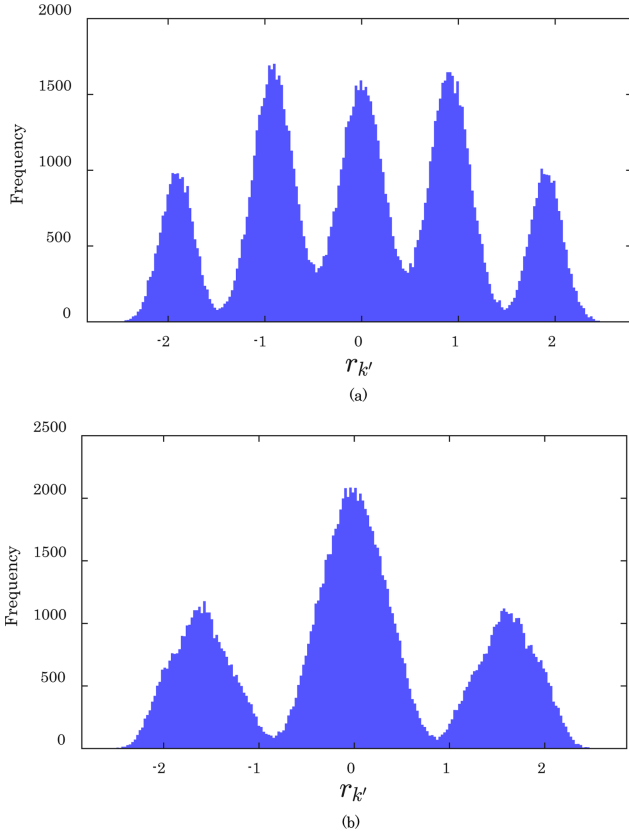
**Fig. 4.** (Color online) Double-track readback signal obtained from two-track simultaneous reading with a wide-track reader.

$PW_{CT50}$ , and in the down-track direction,  $PW_{DT50}$ , where  $PW_{CT50}$  and  $PW_{DT50}$  are 22 nm and 13.5 nm, respectively. These widths imply that the ITI effect is more severe than intersymbol interference (ISI), which is the reason why the two-track reading method using a wide-track reader was chosen for this study. The track pitch (TP) and bit length (BL) were set at 14.75 nm and 22 nm, respectively, with an AD of 2 Tb/in<sup>2</sup>. It is important to note that we can achieve higher ADs by reducing TB or BL. This typically requires the adoption of 2D signal processing techniques. However, in this study, we focus on optimizing the efficiency of 1D detection, and therefore, we have fixed the AD at 2 Tb/in<sup>2</sup>. An example of a double-track readback signal obtained from two-track simultaneous reading with a wide-track reader is shown in Fig. 4, where the red and blue lines were generated by ignoring the magnetization of the lower and upper tracks, respectively. The double-track readback signal was subject to electronic noise,  $n(t)$ , assumed to be additive white Gaussian noise, where its severity was dependent on the signal-to-noise ratio (SNR). In this study, the SNR is defined as:

$$\text{SNR} = 10 \log_{10} \left( \frac{A^2}{\sigma^2} \right) \text{ in decibel (dB)}, \quad (3)$$

where  $A^2$  is the power of the readback signal and  $\sigma$  represents the standard deviation of electronic noise.

The readback signal  $r(t)$  is then sent through a seventh-order Butterworth low-pass filter (LPF), whose cut-off frequency is at  $1/(2 \times \text{BL})$ , to eliminate the out-of-band noise, and is sampled at a time  $t = 0.5k \times \text{BL}$  assuming perfect synchronization, generating  $r_{k'} = r(0.5k \times \text{BL})$ . The centers of the front and rear halves of the recorded magnetization are the sampling points. Next, the sampled sequence  $r_{k'}$  is equalized by a 1D equalizer design based on a minimum mean-squared error approach [9] to adjust the signal to match the desired PR-2 target. The equalized sequence  $z_{k'}$  is then fed to a modified Viterbi detector to



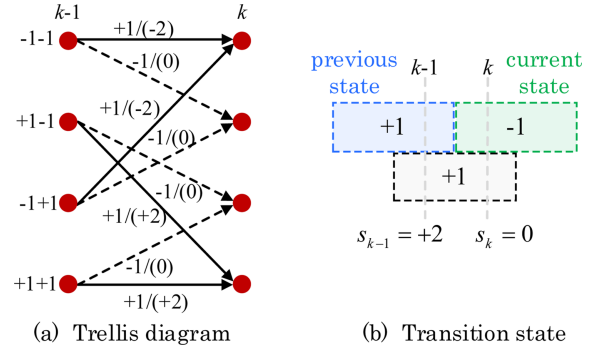
**Fig. 5.** (Color online) Amplitude distributions of the readback signals obtained from oversampling (a) at the bit transitions of each track and (b) at the centers of the front and rear halves of the recorded magnetization, respectively.

estimate the user bits,  $a_k$ .

### 3. Proposed Systems

We start by analyzing the amplitude of the readback signals obtained from the different oversampling schemes when the reader is positioned between two desired tracks, as shown in Fig. 5. The first scheme samples the readback signal at the bit transitions of each track. This means that the sampling interval is equal to  $BL/2$ , where  $BL$  is the written bit length. In the second scheme, the sampling points are located at the centers of the front and rear halves of the recorded magnetization, which also means that the sampling interval is equal to  $BL/2$ . Figs. 5(a) and 5(b) show the amplitude distributions of the readback signals obtained from the first and second oversampling schemes, respectively.

The amplitude distribution of the first sampling scheme contains five data groups, with peak amplitudes located around ‘0,’ ‘ $\pm 1$ ,’ and ‘ $\pm 2$ ,’ as illustrated in Fig. 5(a), which is consistent with the PR-2 channel as explained in



**Fig. 6.** (Color online) (a) Modified Trellis diagram, (b) an example of the transition state of  $\langle +1, +1 \rangle \rightarrow \langle -1, +1 \rangle$ .

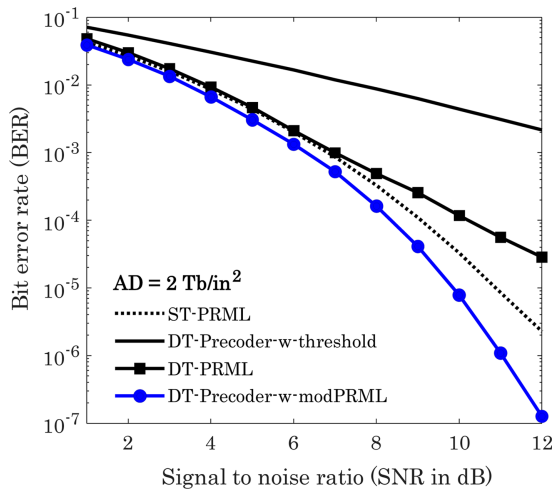
[5]. This verifies that the PRML technique is appropriate for two-track reading with a wide-track reader. In contrast, the second sampling scheme shown in Fig. 5(b) displays three data groups with peak amplitudes located around ‘0’ and ‘ $\pm 2$ ’. This makes it easy to identify which group corresponds to bit ‘+1’ or ‘-1’ using the pre-coder and threshold detector. However, as the AD increases, the effectiveness of this detector may diminish.

Therefore, to enhance the performance of the detection process of the two-track reading with a wide-track reader technique for shingled recording, we propose double-track PRML detection, where the conventional Trellis diagram is modified according to its new state diagram, as shown in Fig. 6(a). In our proposed technique, we utilize a pre-coder along with an oversampling scheme, where the sampling points are located at the centers of the front and rear halves of the recorded bits, as shown in Fig. 6(b). The conventional Trellis diagram has four states in this PR-2 situation [7], so there are eight paths in total. In contrast, the branch metric of our modified Trellis diagram is calculated based on all possible transitions of recorded magnetization according to the oversampling point.

For example, for the transition state  $\langle +1, +1 \rangle \rightarrow \langle -1, +1 \rangle$  as depicted in Fig. 6(b), the magnetization states  $\langle +1, +1, -1 \rangle$  represent the previous state, transition state, and current state, respectively. This transition produces readback amplitudes for the  $k-1$ -th and  $k$ -th bit of  $S_{k-1} = +2$  and  $S_k = 0$ , respectively. The complexity of our proposed detector will remain the same as that of a conventional one; however, it can detect two bits at the same time.

### 4. Performance Evaluation

In this study, we assess the BER performance of the different recording schemes, all at an AD of  $2 \text{ Tb/in}^2$ . These consist of:



**Fig. 7.** (Color online) BER performance versus SNR of various signal processing schemes at an AD of 2 Tb/in<sup>2</sup>.

1) A single-track reading scheme, denoted by “ST-PRML”, which utilized PRML detection to process the retrieved readback signal. The TP and BL were set to 22 nm and 14.75 nm, respectively.

2) A double-track reading scheme using the oversampling detection technique denoted as “DT-Precoder-w-threshold”. The pre-coder and threshold detector were implemented similarly to those proposed in [7].

3) A double-track reading scheme using the double-track PRML detection technique, referred to as “DT-PRML”. Sampling occurs at the bit transition of each track to simultaneously capture both data tracks, similar to the proposals in [7].

4) Our proposed double-track reading scheme is processed using a modified Viterbi detector, referred to as “DT-Precoder-w-modPRML”.

The simulation results show that our proposed detection technique effectively enhances performance in terms of BER compared to the other methods, e.g., single- and double-track reading PRML, and double-track reading threshold detection, as shown in Fig. 7. At a BER of  $10^{-4}$ , the proposed system can achieve gains of approximately 1.3 dB and 2.4 dB compared to the ST-PRML and DT-PRML systems, respectively, outperforming the threshold detection technique. This outcome demonstrates that the modified Viterbi detector can effectively utilize two-track reading with a wide-track reader in SMR systems.

## 5. Conclusions

This study proposes utilizing pre-coding alongside a modified Viterbi detector to enhance detection effectiveness in single-layer magnetic recording systems. The traditional

Trellis diagram of the partial response-2 channel is modified and calculated based on all possible transitions of recorded magnetization according to the oversampling point. In this setup, the sampling points are positioned at the centers of both the front and rear halves of the recorded bits. Before writing the user bits onto the granular media, they must be rearranged using a pre-coder. With an areal density of 2 Tb/in<sup>2</sup>, the track pitch and bit length are set at 14.75 nm and 22 nm, respectively. The proposed double-track partial response maximum likelihood (PRML) system that utilizes a modified Viterbi detector demonstrated superior bit error rate performance compared to single-track PRML systems, double-track reading with a threshold detector, and double-track PRML systems that use a conventional Viterbi detector. However, to enhance the effectiveness of future research, it is essential to explore alternative algorithms, particularly 2D signal processing techniques, across various BL and TP scenarios at higher AD.

## Acknowledgments

This project is partially funded by National Research Council of Thailand (NRCT) under grant number N41A661187 and in part by the School of Integrated Innovative Technology (SIITec), grant number 2568-02-10-003, King Mongkut’s Institute of Technology Ladkrabang (KMITL), Thailand.

## References

- [1] K. S. Chan, R. Radhakrishnan, K. Eason, M. R. Elidrissi, J. J. Miles, B. Vasic, and A. R. Krishnan, *IEEE Trans. Magn.* **46**, 804 (2010).
- [2] R. E. Rottmayer, S. Batra, D. Buechel, W. A. Challener, J. Hohlfield, Y. Kubota, L. Li, B. Lu, C. Mihalcea, K. Mountfield, K. Pelhos, C. Peng, T. Rausch, M. A. Seigler, D. Weller, and X.-M. Yang, *IEEE Trans. Magn.* **42**, 2417 (2006).
- [3] J. G. Zhu, X. Zhu, and Y. Tang, *IEEE Trans. Magn.* **44**, 125 (2008).
- [4] R. Wood, *J. Magn. Magn. Mater.* **561**, 169670 (2022).
- [5] S. Nabavi and B. V. K. V. Kumar, *IEEE ICC*, Glasgow, UK, 6249 (2007).
- [6] S. Karakulak, P. H. Siegel, J. K. Wolf, and H. N. Bertram, *IEEE Trans. Magn.* **46**, 3639 (2010).
- [7] H. Muraoka and S. Greaves, *IEEE Trans. Magn.* **51**, 3002404 (2015).
- [8] M. Yamashita et al., *IEEE Trans. Magn.* **47**, 3558 (2011).
- [9] P. Kovintavewat, I. Ozgunes, E. Kurtas, J. R. Barry, and S. W. McLaughlin, *IEEE Trans. Magn.* **38**, 2340 (2002).