Numerical optimization of writer geometries for bit patterned magnetic recording

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A fully-automated pole-tip shape optimization tool, involving write head geometry construction, meshing, micromagnetic simulation and evaluation, is presented. Optimizations have been performed for three different writing schemes (centered, staggered and shingled) for an underlying bit patterned media with an areal density of 2.12 Tdots/in². Optimizations were performed for a single-phase media with 10 nm thickness and a magnetization gradient of 8 nm. From the computed write field and its gradient and the minimum energy barrier during writing for islands on the adjacent track, the overall write error rate is computed. The overall write errors are 0.7, 0.08, and 2.8 × 10⁻⁵ for centered, staggered, and shingled writing.

Keywords: bit patterned media, bit error rate, numerical optimization, shape optimization, micromagnetic simulation

I. INTRODUCTION

Bit patterned magnetic recording poses many novel challenges, in terms of media manufacturing but also in terms of the recording physics. Bit patterned magnetic recording requires a localized write field. Good down-track field gradients are important for island addressability. Good cross-track field gradients are needed to support the high track density. The distribution of the write field strongly depends on the pole tip shape and shield distances. For best writer performance both the effective write field and the write field gradient should be maximized. In addition the effective write field should be small enough to avoid adjacent track erasure. Therefore, finding the best writer design is a constrained multi-objective optimization problem in a high dimensional configuration space, which grows in dimensions the more design parameters are taken into account. Multiple sweeps of a single design parameter are numerically too expensive to find the optimal solution.

We combine micromagnetic finite element simulations2 with a numerical optimization tool for multi-objective optimization. The combination of finite element analysis with optimization has a long tradition in the automotive industry4 and electrical engineering. Fukuda and co-workers1 simultaneously optimized writer and media parameters for granular perpendicular recording, using a genetic algorithm together with a finite element static Maxwell solver and a micromagnetic solver.

We focus on writer optimization for bit patterned media. Numerical optimization methods are iterative and require many evaluations of the objective function. In order to reduce the number of finite element micromagnetic field evaluations, we apply the response surface method3 that locally approximates the objective functions.

Bit patterned media is a candidate for extending magnetic data storage towards 10 Tb/in² and many papers have been published showing its potential.1,2,6,7,10,12,13 Writing on continuous granular media, where a bit cell is formed by a large group of grains, no loss of information appears if a few grains are not switched by the write field. But looking at bit patterned media, where each bit cell is formed by just one single island, we now have to assess if switching has occurred and introduce bit error rates.5 In order to analyze the performance, we can use multiple micromagnetic simulations of bit patterned media ensembles1 and count the write errors or a statistical approaches to compute the write error rate.5 In this paper we aim for the statistical approach. In section II of this paper we describe the recording head geometry, the media design and the iterative optimization process. Section III shows the optimized head structures for each writing scheme (centered, staggered and shingled writing), their performance and bit error rates.

II. METHOD

The optimization cycle consists of two major parts. The model calculation constructs and analyzes a write head model according to a given set of design parameters, and the iterative optimization process, which suggests new sets of design parameters based on the previous results.

The calculation of a model is performed by a Python script, which reads in given design parameters and produces a write head geometry accordingly. The model con-
sists of a full write head structure with coils and a soft underlayer (Section II A). The script meshes the model, performs a micromagnetic simulation and extracts and evaluates the simulation results. The algorithm can run fully automatically. Computer aided design is done with the software package Salome (12). Meshing with fine mesh near the pole tip (2.5 nm) is done with the mesh generation program Netgen (13). A hybrid finite element / boundary element solver (2) was used for write field calculation.

After bringing the write head into a remanent state we apply an 80 mA coil current pulse with a rise time of 0.1 ns. After 2 ns we compute the write field below the saturated write head with a resolution of 2.5 nm. Evaluation of fields and gradients are done in the center of the target track and the center of the adjacent track.

A. Head design

The write head geometry is constructed according to design parameter ranges (see figure 1): trailing shield gap [5 nm, 20 nm], side shield gap [5 nm, 20 nm], pole tip trailing edge angle [0, π/4], pole tip cross track angle [0, π/4], pole tip width [10 nm, 30 nm], and cross track offset [-10 nm, 10 nm]. The interval gives the possible range of a parameter. For shingled writing the pole tip width is fixed to 80 nm and a skewing angle of π/12 is used. The write head is constructed with a helical coil with 4 turns. For the main pole we use a magnetic polarization of 2.4 T and an exchange constant of 20.15 pJ/m. The shields have a magnetic polarization of 2 T and an exchange of 13 pJ/m. The distance between the air bearing surface and soft under layer is 20 nm.

B. Media design

While the pole tip shape and the shield distances vary, a predefined bit patterned media layout is used as shown in figure 2. Single phase cylindrical dots with a diameter of 12 nm were used as the target media. Separated by a cross track pitch of 19 nm and a down track pitch of 16 nm, which gives us a media layout with an overall areal density at 2.12 T dots/in².

Design parameters were optimized for three different writing schemes: centered writing, staggered writing and shingled writing. Centered writing is the classical writing scheme and focuses on one track center only. The staggered writing scheme (14) gives the opportunity to increase the pole tip size so that the write field is focused above two tracks. The write head has to switch twice as fast as for the centered or shingled writing scheme. The write head for shingled writing (10) is built so that only one of its corners writes on a track.

C. Optimization

The optimization software suggests a set of design parameters and performs the script execution (model calculation). The optimizer reads in the results which represent the performance of the write head and suggests a new set of design parameters based on a multi-objective search algorithm (3), which uses a non-dominated sorting scheme to rank designs. The two objective functions are $f_1 = \frac{dH_{\text{eff}}}{dx}$ (maximize field gradient) and $f_2 = H_{\text{eff}}(x_{\text{max}})$. $x_{\text{max}}$ is the position where $\frac{dH_{\text{eff}}}{dx}$ reaches its maximum. Furthermore, we keep the effective field along the adjacent track below a certain value with a constraint in order to avoid adjacent track erase. The iterative procedure is repeated until there is no significant improvement in the solution or a predefined number of evaluations (500 iterations) have been executed.

D. Evaluation of write error rate

In order to calculate the total write error rate (5), we add the following contributions: (1) not switching the
1. RESULTS AND DISCUSSION

In table I we show bit error rates for each writing scheme where we only changed the coercive field of the media by shifting the working point in the field profile. Thermally induced adjacent track erasure is dominating for centered and staggered writing. Higher anisotropy media (higher $H_C$) improves $BER_{adj}$ but reduces the writeability at the target bit. Table II shows the optimal design parameters of each head.

The results show that bit patterned media recording on single phase islands and a magnetic spacing of 8 nm can only be achieved with shingled writing. For shingled writing an optimal write field profile (see Fig. 3) was found. Through optimization the point of maximum field gradient moved towards the point of maximum write field. Thus both on-track errors and cross track errors were reduced. All errors have the same order of magnitude.

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**TABLE I.**

| writing scheme | $H_A [T]$ | $\frac{dH_{eff}}{dx} [\text{mT}/\text{nm}]$ | $BER_{targ}$ | $BER_{prev}$ | $BER_{adj}$ |
|----------------|-----------|------------------------------------------|--------------|--------------|-------------|
| centered       | 0.75      | 33                                       | 1.3x10^{-5}  | 5.5x10^{-5}  | > 1         |
| staggered      | 0.90      | 27                                       | 1.9x10^{-2}  | 9.4x10^{-7}  | 5.5x10^{-1} |
| staggered      | 0.82      | 38                                       | 1.3x10^{-6}  | 4.7x10^{-6}  | > 1         |
| shingled       | 1.07      | 27                                       | 2.9x10^{-5}  | 7.2x10^{-8}  | 5.2x10^{-2} |
| shingled       | 1.10      | 34                                       | 1.4x10^{-4}  | 2.3x10^{-6}  | 2.7x10^{-8} |

**TABLE II.**

| writing scheme | pole tip width [nm] | cross track angle [°] | trailing edge angle [°] | shield gap [nm] | side shield gap [nm] | trailing gap [nm] |
|----------------|---------------------|-----------------------|------------------------|----------------|---------------------|------------------|
| centered       | 14                  | 45                    | 5                      | 10             | 5                   | 14               |
| staggered      | 13                  | 35                    | 10                     | 20             | 5                   | 16               |
| shingled       | 9                   | 16                    | 15                     | 20             | 12                  | 14               |
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