Determination of coupling state in a Dual-FGL STO using injection locking

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We studied a dual-field generation layer spin-torque oscillator (dual-FGL STO) in an HDD head using a newly established analysis method based on *injection locking*. The dual-FGL STO is designed to induce the coupled oscillation of the dual-FGL for higher performance in microwave-assisted magnetic recording (MAMR). However, direct evidence of the coupled oscillation has not been obtained yet. Here, we report that injection locking, which is synchronization between STO oscillation and external microwave input, enables clear differentiation between the coupled and non-coupled oscillation state. We used a microwave magnetic field (H_{MW}) from a coplanar waveguide and observed resistance modulation only in the non-coupled oscillation state because the coupled state is insensitive to H_{MW}. These results demonstrate that the injection locking method is useful for studying spintronic devices and that the dual-FGL STO realizes the coupled oscillation state in the HDD head for MAMR.

***Index Terms*— Dual field generation layer (dual-FGL), hard disk drive (HDD), injection locking, microwave-assisted magnetic recording (MAMR), spin-torque oscillator (STO)**

I. Introduction

MICROWAVE-ASSISTED magnetic recording (MAMR) is one of the next key technologies in hard disk drives (HDDs) [1, 2]. In MAMR, a spin-torque oscillator (STO) fabricated in the write gap of an HDD head generates a microwave magnetic field, which assists magnetization switching in recording media (microwave-assisted switching, MAS). In order to maximize the recording capacity of HDDs by MAMR, the development of STO optimized for MAMR is required.

Recently, we have focused on an STO with two oscillation layers (field generation layers, FGLs) that we call dual-FGL STO [3-5]. The dual-FGL is aiming at anti-parallelly coupled oscillation of the magnetizations due to their dipolar field. With the coupled oscillation mode, the dual-FGL STO provides a focused microwave field oscillating in the media plane with smaller interaction with the main pole and trailing shield, which are the desired conditions for recording density improvement with MAMR.

In previous studies, we measured the dual-FGL STO fabricated in HDD heads [5-7]. To confirm its oscillation, we have conducted a conventional measurement, which measures the oscillation of giant magnetoresistance (GMR) caused by the oscillation of magnetization. Although we observed an oscillation peak [5], the spectrum itself did not indicate whether it originated from the coupled oscillation and could not exclude other possibilities, such as non-coupled oscillation. Only micromagnetic simulation results, which show oscillation frequency and bias current dependence consistent with the experiment, support the realization of the coupled oscillation state [5]. We also measured recording performance using the dual-FGL STO and confirmed the improvement due to the MAS effect [6, 7]. However, we have not extracted the indication of the coupled oscillation from those results. Other evidence that directly proves the coupled oscillation is desired.

In this study, we report clear differentiation between the coupled and non-coupled oscillation state using a novel analysis method based on injection locking. The analysis method has been proposed for studying oscillation states in STOs, which is applicable to HDD heads [8, 9]. By applying an external microwave magnetic field (H_{MW}) to the STO (Fig. 1a), the resistance is modulated when the STO oscillation is synchronized to the microwave field, which tells us the detailed properties of the oscillation state [9]. As we discuss later, the coupled oscillation state in the dual-FGL STO is insensitive to the external field, and no resistance modulation occurred despite the clear spectrum peak in the conventional spectrum experiment. On the contrary, when we intentionally induced a non-coupled oscillation state, which is a single oscillation of an FGL, we observed clear modulation in resistance at the same frequency as the spectrum peak. With these results, we can conclude that the coupled oscillation state is realized in the dual-FGL STO, which can be identified with the injection locking method.

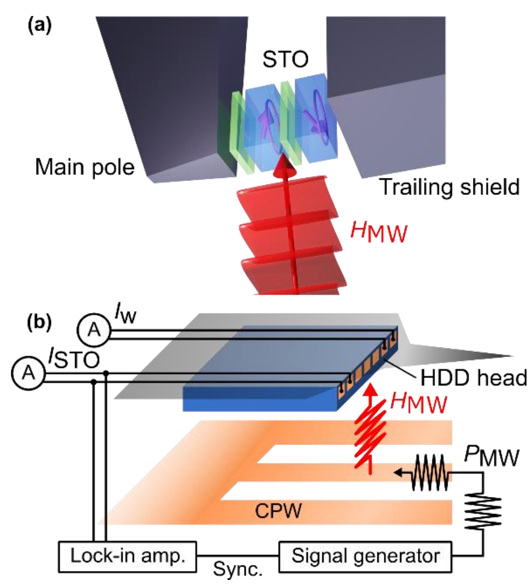

Fig. 1. Analysis method based on injection locking. Schematic figures of (a) the dual-FGL STO in the write gap and (b) experimental setup.

II. EXPERIMENTAL SETUP

We prepared a coplanar waveguide (CPW) with a 3-µm-wide signal line, which emits H_{MW} by applying a microwave signal. The HDD head was attached to a suspension, and it was aligned at the center of the CPW. During the alignment, we applied a low-frequency (1,013 Hz) signal to the CPW and monitored the output from the reader element in the HDD head.

In the injection locking experiment (Fig. 1b), we applied coil current I_w and STO bias current I_{STO} to the HDD head. The microwave signal was generated with a 50% duty with a modulation frequency of 1 kHz. While we changed the frequency of the microwave signal (f_{MW}), we measured resistance modulation in the STO (ΔR_{STO}) synchronized to the modulation of the microwave signal.

For the conventional spectrum experiment, we employed the same setup as in the previous study [5]. We obtained the intensity of the GMR oscillation at each frequency (f_{STO}).

III. RESULTS

Figures 2a and 2b show the results of the conventional spectrum experiment at I_{STO} = -5.0 and +3.0 mA, respectively. The positive bias (Fig. 2b) can induce the coupled oscillation for MAMR. On the other hand, using the negative bias (Fig. 2a), we can expect a single oscillation of an FGL, that is, a non-coupled oscillation state. However, the peak frequency was similar to each other. We could not distinguish the oscillation states from the conventional spectrum measurements.

Figures 2c and 2d show the results of the injection locking experiment, which is f_{MW} dependence of ΔR_{STO}, where I_{STO} = -5.0 and +3.0 mA as same as in Fig. 2a and 2b, respectively. In Fig. 2c, we observed an increase followed by a decrease of ΔR_{STO} as f_{MW} crosses the oscillation frequency in Fig. 2a, which is the injection locking signal [9]. In Fig. 2d, however, such injection locking signal was absent despite the similar spectrum peaks in Fig. 2b to Fig. 2a.

Based on these results, we successfully confirmed the coupled oscillation as the state in which we can observe a peak in the conventional spectrum experiment without the appearance of any signal in the injection locking experiment.

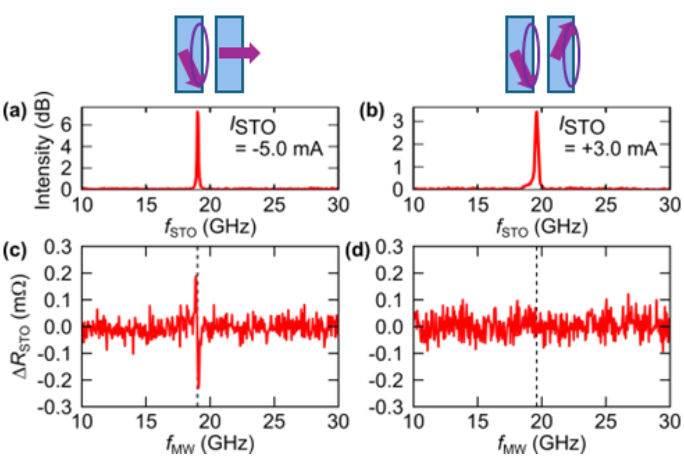

Fig. 2. Experimental results. (a), (b) GMR spectrum at I_{STO} = -5.0 and +3.0 mA, respectively. (c), (d) Injection locking results at I_{STO} = -5.0 and +3.0 mA, respectively.

IV. DISCUSSION

The results above enable us to confirm the coupling state experimentally. Here, we discuss its mechanism by referring to the micromagnetic simulation results. As shown in Fig. 3, we reproduced the experimental results, where only the single-FGL oscillation shows injection locking.

In the locking state of the single-FGL oscillation, we confirmed that the magnetization of the FGL and H_{MW} are locked into the same phase. Therefore, there is a gain in Zeeman energy in the system, and modification of f_{STO} is preferred.

On the other hand, in the coupled oscillation state, its anti-parallel configuration of the FGL magnetizations cancels out such Zeeman energy gain. The system prefers the STO oscillation with its original frequency, and the injection locking is difficult to occur.

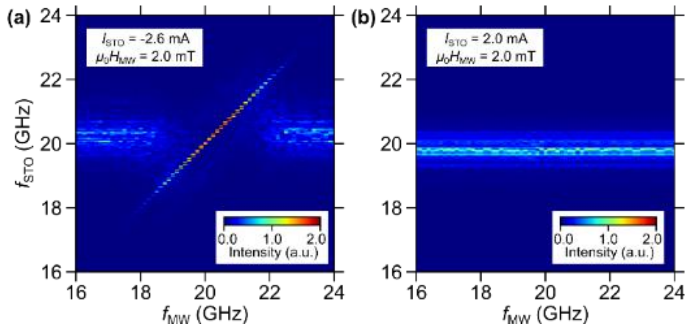

Fig. 3. Simulation results. (a), (b) Locking phenomena of f_{STO} to f_{MW} at I_{STO} = -5.0 and +3.0 mA, respectively.

V. CONCLUSION

With the injection locking method, we observed a clear difference between oscillation states, which is attributed to the different coupling states, and thus confirmed the coupled oscillation state in the dual-FGL STO. This method is applicable to product-level HDD heads and other spintronic devices, enabling the detection and study of their coupling states.

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