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ABSTRACT
The magnetization dynamics in a spin torque oscillator (STO) consisting of two in-plane magnetized free layers is studied by solving the Landau-Lifshitz-Gilbert equation and evaluating the Lyapunov exponent numerically. The phase diagrams of the oscillation frequencies of the magnetizations and magnetoresistance and the maximum Lyapunov exponent are obtained from the numerical simulations. The phase synchronization is found in the low current region, whereas the magnetizations oscillate with different frequencies in the middle current region. On the other hand, positive Lyapunov exponents found in the high current region indicate the existence of chaos in the STO.

I. INTRODUCTION
Spin torque oscillator (STO) is a nonlinear oscillator in nanoscale, and generates an oscillating power having the frequency on the order of gigahertz through giant or tunnel magnetoresistance (MR) effect.1–3 A conventional structure of STO consists of three ferromagnets, called free, reference, and pinned layers, with a nonmagnetic spacer between the free and reference layers. The magnetization direction in the reference layer is fixed by the pinned layer, whereas that in the free layer can change its direction by applying magnetic field and/or electric current.

Recently, however, another type of STO has been proposed for a new scheme of magnetic recording,4 namely microwave assisted magnetization reversal (MAMR).5–16 In MAMR, microwave magnetic field is emitted from an STO to a magnetic recording media and induces an oscillation of the magnetization in a recording bit, resulting in a reduction of a direct field for recording. At the beginning of the study on MAMR, the STO consisted of an in-plane magnetized free layer and perpendicularly magnetized reference and pinned layers.8,17–21 The structure of such an STO becomes, however, thick to make the magnetizations in the reference and pinned layers perpendicular.8,22,23 The latest design of the STO for MAMR consists of two in-plane magnetized ferromagnets called field-generation layer and spin-injection layers.8 The field-generation layer acts as a microwave source for MAMR, whereas the spin-injection layer provides spin current into the field-generation layer to excite an auto-oscillation of the magnetization. It should be emphasized that this type of STO does not have a pinned layer to make the recording head thin. Therefore, both two ferromagnets can be regarded as free layers. A coupled motion of two ferromagnets in nanostructured multilayers is a recent exciting topic in magnetism.22 For MAMR application, a theoretical study to clarify the dynamical phase in this STO over a wide range of the electric current is necessary, while an experimental work has been reported recently.23

In this paper, a theoretical study on the magnetization dynamics in an STO with two free layers is presented. We solve the Landau-Lifshitz-Gilbert (LLG) equation numerically, and evaluate the Lyapunov exponent to characterize the dynamical phase. A phase synchronization is found in the low current region, whereas two magnetizations oscillate with different frequencies in the middle current region. On the other hand, chaos is found in the high current region, which is identified from positive Lyapunov exponents.

II. SYSTEM DESCRIPTION
The STO studied in this work consists of two ferromagnets, F_k (k = 1, 2), separated by a thin nonmagnetic spacer.22,23 In the recent experiment,23 the F_1 and F_2, corresponding to the field-generation
and spin-injection layers, respectively, were CoFe and NiFe, whereas the nonmagnetic spacer was Ag. The z axis is perpendicular to the film plane, whereas the x and y axes lie in the plane. The unit vector pointing in the magnetization direction of the Fk layer is denoted as \( \mathbf{m}_k \). The dynamics of \( \mathbf{m}_k \) is described by the LLG equation,

\[
\frac{d\mathbf{m}_k}{dt} = -\gamma_k \mathbf{m}_k \times \mathbf{H}_k + \alpha_k \mathbf{m}_k \times \frac{d\mathbf{m}_k}{dt} - \frac{\gamma \hbar p_j}{2e(1 + p_j^2 \mathbf{m}_k \cdot \mathbf{m}_j)M_0 d_k} \mathbf{m}_k \times (\mathbf{m}_2 \times \mathbf{m}_1),
\]

where \( \gamma_k \) and \( \alpha_k \) are the gyromagnetic ratio and the Gilbert damping constant, respectively. The saturation magnetization and thickness of the Fk layer are denoted as \( M_k \) and \( d_k \). Since the magnetic recording is achieved by applying a direct magnetic field generated in the recording head close to the STO to the recording media, the magnetization dynamics in the STO is also affected by a direct field.\(^{23,24}\) Thus, an applied field should be taken into account in the magnetic field in the LLG equation. The magnetic field consists of the applied field \( H_{app} \) in the z direction, the demagnetization field, and the dipole field as

\[
\mathbf{H}_k = \begin{pmatrix} -4\pi M_k N_{kx} m_{kx} - H_{dk} m_{kx} \\ -4\pi M_k N_{ky} m_{ky} - H_{dk} m_{ky} \\ H_{app} = 4\pi M_k N_{kz} m_{kz} + 2H_{dk} m_{kz} \end{pmatrix}.
\]

The demagnetization coefficient \( N_{ki} \) is evaluated from their analytical solutions as \([(k, k') = (1, 2) \text{ or } (2, 1)]\)\(^{25,26}\)

\[
N_{kx} = \frac{1}{\tau_k} \left\{ \frac{4}{3\pi} - \frac{4}{3\pi} \sqrt{1 + \tau_k^2} \right\} t_k K \left( \frac{1}{\sqrt{1 + \tau_k^2}} \right) + \left( 1 - t_k^2 \right) E \left( \frac{1}{\sqrt{1 + t_k^2}} \right) + \tau_k,
\]

\[
H_{dk} = \pi M_k \left[ \frac{d_k}{r_k^2 + d_k + d_{k'}} - \frac{d_k}{r_k^2 + \left( \frac{d_k}{r_k} \right)^2} \right],
\]

where \( r_k = d_k/(2r) \) with the radius \( r \) and \( d_\mathbf{N} \) is the thickness of the nonmagnet, whereas \( K(\kappa) \) and \( E(\kappa) \) are the first and second kinds of complete elliptic integrals with the modulus \( \kappa \). The last term in Eq. (1) is the spin-transfer torque, where \( j \) is the current density whereas \( p_j \) corresponds to the spin polarization. The positive current is defined as the electrons flowing from the F1 to F2 layer. We note that two magnetizations are coupled via the spin-transfer effect and the dipole field.

The values of the parameters are derived from CoFe/Ag/NiFe trilayer\(^{27}\) as \( M_1 = 1720 \text{ emu/cm}^2, M_2 = 800 \text{ emu/cm}^2, \alpha_1 = 0.006, \alpha_2 = 0.010, d_1 = 5 \text{ nm}, d_2 = 3 \text{ nm}, p_1 = p_2 = 0.3, \) and \( y = 1.764 \times 10^7 \text{ rad/(Oe s)} \). The magnitude of the microwave magnetic field generated by a ferromagnet having the saturation magnetization as such is on the order of 100 Oe,\(^{28}\) which is sufficient to achieve MAMR experimentally.\(^{10}\) The thickness of the nonmagnet is 5 nm, whereas the radius is 50 nm. The applied field is 8.0 kOe. Since the spacer layer consists of a metal (Ag) in the experiment,\(^{29}\) a large current density on the order of \( 10^8 \text{ A/cm}^2 \) can be injected. The LLG equation was solved by the 4th-order Runge-Kutta scheme with a constant time step of \( \Delta t = 10^{-9} \text{ ns} \) for all simulation. In the present simulation, we first solved the LLG equation without current to relax the magnetizations to their energetically stable states. After that, the LLG equation in the presence of a finite current was solved for time range of 0.5 \( \mu s \) to investigate the magnetization dynamics driven by spin-transfer torque. The time necessary to reach a stable oscillation is, typically, on the order of 1 ns.

The magnetization dynamics in an STO is detected through the giant or tunnel magnetoresistance (MR) effect in the experiment,\(^ {23} \) which depends on \( m_1 \cdot m_2 \). On the other hand, the microwave field required in MAMR reflects the oscillations of the magnetizations, \( m_1 \) and \( m_2 \). Therefore, we calculate the peak frequencies of the Fourier spectra of \( m_{1x}, m_{2x}, \) and MR \( \equiv m_1 \cdot m_2 \) in the following.

### III. SYNCHRONIZATION AND CHAOS

Figure 1(a) shows typical dynamics of \( m_1 \) (red) and \( m_2 \) (blue) in a low current region. The auto-oscillations of the magnetizations around the z axis are excited in two ferromagnets. The time evolutions of \( m_{1z} \) (red dotted), \( m_{2z} \) (blue dashed), and MR (black solid) are also shown in Fig. 1(b). It can be seen that two magnetizations oscillate with an identical frequency, i.e., a frequency synchronization is excited. Since the relative angle between the magnetizations is temporally constant in the synchronized state, the MR is also constant. In this case, no oscillating signal will be detected through the MR effect. In fact, the power spectrum density of an STO in a low current region was found to be zero experimentally.\(^{23}\) However, no electric signal does not necessarily mean the absence of the auto-oscillations of the magnetizations. We believe that the synchronized oscillation is excited in the low current region, and it will be applicable to MAMR application because the field-generation layer (F1) shows the oscillation, and therefore, emits microwave field.

One might consider that the microwave magnetic field generated outside the STO becomes zero because two magnetizations oscillate with almost antiphase; see Fig. 1(b). It should be, however, noted that the magnitude of the magnetic field generated by the oscillating magnetization is proportional to the saturation magnetization. Since the saturation magnetizations of two ferromagnets in the present STO are largely different, the total microwave magnetic field remains finite even though two ferromagnets oscillate with antiphase.

Figure 1(c) shows typical dynamics in the middle current region. In this case, two magnetizations oscillate with different frequencies. Therefore, the MR also shows an oscillation, where its frequency is the difference of the frequencies in two magnetizations. It should be noted that the oscillation of the MR can be detected experimentally in this region. The oscillation frequency of the MR shows redshift as discussed below, which is consistent with the experiment.\(^{23}\) It should be emphasized that this region is also applicable to MAMR because the F1 layer shows an auto-oscillation with a unique frequency.

A further increase of the applied current density leads to complex dynamics of the magnetizations. Figures 1(d) and 1(e) respectively show the dynamical trajectories of \( m_1 \) and \( m_2 \) in a high current region \( (j = 4.0 \times 10^8 \text{ A/cm}^2) \) after the magnetizations move to an
FIG. 1. (a) Dynamical trajectories of $m_1$ (red) and $m_2$ (blue) in a steady state at $j = 0.1 \times 10^8$ A/cm$^2$. (b) Time evolutions of $m_{1x}$ (red dotted), $m_{2x}$ (blue dashed), and MR (black solid) at $j = 0.1 \times 10^8$ A/cm$^2$. Note that the range in the horizontal axis differs from that in (b). (c) Time evolutions of $m_{1x}$, $m_{2x}$, and MR at $j = 2.0 \times 10^8$ A/cm$^2$. (d), (e) Dynamical trajectories of $m_1$ (red) and $m_2$ (blue) at $j = 4.0 \times 10^8$ A/cm$^2$, respectively. (f) The trajectories in the reduced phase space, $(m_{kx}, m_{ky})$ at $j = 4.0 \times 10^8$ A/cm$^2$. (g) Time evolution of MR at $j = 4.0 \times 10^8$ A/cm$^2$. (h) Fourier spectra of $|m_{1x}|$ (red), $|m_{2x}|$ (blue), and $|MR|$ (black) at $j = -4.0 \times 10^8$ A/cm$^2$, respectively. (i) Time evolution of MR at $j = -4.0 \times 10^8$ A/cm$^2$.

attractor, where the data in last 10 ns are used for the plots. The trajectories in the reduced phase space, $(m_{kx}, m_{ky})$, are also shown in Fig. 1(f). The time evolution of MR is also shown in Fig. 1(g). As can be seen in these figures, highly nonlinear dynamics appears in two layers, and the MR does not show periodicity. We note that highly nonlinear dynamics as such was found in STOs with two ferromagnets in the previous works. For example, Kudo et al. performed numerical simulations of the LLG equation for two in-plane magnetized ferromagnets with in-plane magnetic anisotropy, where the ferromagnets are coupled via spin-transfer effect only, and found chaotic dynamics of the magnetizations. We identify chaos in the present STO by evaluating Lyapunov exponent by using the Shimada-Nagashima method, where the Lyapunov exponent is defined as an average of instantaneous expansion rates of two dynamical trajectories having different initial conditions at $t = t_0$ as

$$\lambda = \lim_{N \to \infty} \frac{1}{N \Delta t} \sum_{n=1}^{N} \frac{1}{\epsilon} \log \left| \frac{\epsilon + \delta(t_0 + n \Delta t)}{\epsilon} \right|,$$

where $\epsilon$ is a perturbation applied to the STO at $t = t_0$, whereas $\delta(t + n \Delta t)$ is the expansion of the perturbation after time $n \Delta t$. In this work, we introduce a four-dimensional phase space with the variables $(\theta_1, \varphi_1, \theta_2, \varphi_2)$ defined as $m_k = (\sin \theta_k \cos \varphi_k, \sin \theta_k \sin \varphi_k, \cos \theta_k)$, and add the perturbation $\epsilon = 1.0 \times 10^{-5}$ rad to the phase space. Then, the (maximum) Lyapunov exponent is obtained from Eq. (5). For example, the Lyapunov exponent of the dynamics shown
in Figs. 1(d)–1(f), where \( j = 4.0 \times 10^8 \, \text{A/cm}^2 \), is a positive value of 6.69 GHz, indicating that the dynamics is chaos. We also note that a large current does not necessarily guarantee chaos. For example, the dynamical trajectories for the opposite current, \( j = -4.0 \times 10^8 \, \text{A/cm}^2 \), look similar to those shown in Figs. 1(d) and 1(e). In addition, the Fourier spectra of \( m_{1z} \), \( m_{2z} \), and \( \text{MR} \) at \( j = -4.0 \times 10^8 \, \text{A/cm}^2 \) have multipeak over wide range of frequency, as shown in Fig. 1(h). However, the time evolution of the MR shown in Fig. 1(i) shows periodicity. In such a case, the Lyapunov exponent is zero.

It is considered that chaos is caused by the large spin-transfer torque. Note that the spin-transfer torques act asymmetric to two ferromagnets; for example, for a positive current, the spin-transfer torque acting on the F\(_1\) layer prefers the antiparallel alignment of the magnetizations, whereas that acting on the F\(_2\) layer prefers the parallel one. As a result, for a large current, the magnetizations cannot stay in limit cycle oscillations, and chaos is excited. The threshold necessary to cause chaos increases with increasing the field magnitude because the damping torques due to the field act symmetric to the magnetizations.

IV. PHASE DIAGRAM

Here, let us summarize the magnetization dynamics studied in Sec. III.

Figure 2(a) summarizes the current dependences of the oscillation frequency of \( m_{1z} \) (red square), \( m_{2z} \) (blue triangle), and \( \text{MR} \equiv \text{m}_1 \cdot \text{m}_2 \) (black circle). Around zero current, two magnetizations show synchronization, i.e., the oscillation frequencies of the magnetizations are identical. As a result, the MR does not show an oscillation. Therefore, the magnetization oscillation will not be detected by an experiment utilizing the MR effect. However, it should be emphasized that this current region will be applicable to MAMR because the magnetization oscillation is excited. In the middle current region, two magnetizations oscillate with different frequencies. When two magnetizations oscillate in the same direction (clockwise or counterclockwise with respect to the z axis), the frequency of MR is the difference between those of two magnetizations. Therefore, the frequency of MR decreases with increasing the current in the positive current region. On the other hand, when two magnetizations oscillate in the opposite direction, the frequency of MR is the sum of those of two magnetizations, which can be found in a narrow region of negative current. The frequency of the MR mainly shows redshift, which is consistent with the experiment. Similarly to the small current region, the magnetization dynamics in the middle current region is also applicable to MAMR, where the oscillation frequencies of two magnetizations are different, and therefore, the MR shows an oscillation. On the other hand, complex dynamics are found in the high current region, where the oscillation frequencies of \( m_1 \) and MR are not uniquely determined.

Figure 2(b) summarizes the Lyapunov exponent as a function of the current density. The Lyapunov exponent in the low and middle current regions are zero, indicating that the magnetization dynamics are sustainable and periodic, as confirmed by the dynamical trajectories in Figs. 1(a)–1(c). The positive Lyapunov exponents appear in the high current region, indicating the existence of chaos in the present STO. Interestingly, the Lyapunov exponent is always positive in the high positive current region, whereas it becomes either positive or zero in the high negative current region. The abrupt changes of the Lyapunov exponent between zero and positive in the negative current region are similar to those often found in chaos system, and indicate the appearance of multi-periodic or quasi-periodic limit cycle. Note that the magnetization dynamics in the high negative current region is highly nonlinear and complex, although the dynamics is periodic, and thus, the Lyapunov exponent is zero, as mentioned above and shown in Figs. 1(h) and 1(i). Therefore, an oscillation frequency is not well-defined even in the region having the zero Lyapunov exponent.

The results shown in Figs. 2(a) and 2(b) indicate that the present STO is applicable to many kinds of practical devices. For example, as repeated, the auto-oscillations of the magnetizations in the low and middle current regions are applicable to MAMR, or more widely, microwave generators. The wide frequency tunability by the current found in Fig. 2(a) is an advantage for the application of the microwave generator. We note that the previous experiment on MAMR\(^2\) focused on the negative current region, where the electrons flow from the F\(_2\) to F\(_1\) layer. However, Fig. 2(a) indicates

![FIG. 2](https://www.aip.org/about/scitation/journals/adv) (a) Current dependences of the oscillation frequencies of F\(_1\) (red square), F\(_2\) (blue triangle), and MR (black circle). The low (yellow-shaded) and middle (green-shaded) current regions correspond to the synchronization and oscillations with different frequencies. The high (blue-shaded) current region corresponds to highly nonlinear dynamics. (b) Lyapunov exponent as a function of the current density.
that the positive current region might be suitable for MAMR because it has a wide range of the current for the auto-oscillation.

The magnetization dynamics in the high current region is not applicable to MAMR nor, more generally, microwave generator because the oscillation frequency of the magnetization is not a unique value. However, the dynamics might be applicable to other applications. For example, chaos having a positive Lyapunov exponent might be used to random number generator. Also, the dynamics between chaos and other dynamical phases will be of great interest for brain-inspired computing, such as reservoir computing. This is because highly nonlinear, not a simple auto-oscillation found in the low current region, is necessary for the brain-inspired computing, whereas chaos should be avoided to guarantee the reproducibility of the computation against noise.

V. CONCLUSION

In conclusion, the magnetization dynamics in an STO with two in-plane magnetized free layers was investigated by solving the LLG equation numerically and evaluating the Lyapunov exponent. The phase synchronization appears in the low current region, whereas the magnetizations oscillate with different frequencies in the middle current region. These dynamics will be applicable to MAMR. On the other hand, the dynamics becomes highly nonlinear in the high current region. The positive Lyapunov exponent found in this region indicated the existence of chaos in the present STO.

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