Magnetization switching by microwaves initially rotating in opposite direction to precession

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A common understanding of magnetization switching in microwave-assisted magnetization reversal is that the rotation direction of the microwaves should be the same with the precession direction of the magnetization. In this letter however, we show that microwaves initially rotating opposite to the magnetization precession destabilize the magnetization at an equilibrium and induces the switching more efficiently, when the microwave frequency depends on time. This argument is analytically deduced from energy balance equation. We also establish a model satisfying this condition, and confirm magnetization switching solely by microwaves by using numerical simulation.

When a rotating magnetic field originating from microwaves is applied to a ferromagnet, and the microwave frequency satisfies certain conditions, the ferromagnet efficiently absorbs energy from the microwaves, and the magnetization switches its direction from one stable state to the other. This phenomenon is called microwave-assisted magnetization reversal and has attracted much attention because of its advantageous writing scheme in magnetic recording media.\(^1\text{–}^{15}\) Microwave-assisted magnetization reversal has been confirmed by both experiments and numerical simulations.

A common understanding of microwave-assisted magnetization reversal is that the rotating direction of the microwaves should be same as the precession direction of the magnetization. Note that the precession direction of the magnetization is determined by the field torque, \(-\gamma \mathbf{m} \times \mathbf{H}\), acting on the magnetization, where \(\gamma\), \(\mathbf{m}\), and \(\mathbf{H}\) are the gyromagnetic ratio, the unit vector along the magnetization direction, and the magnetic field, respectively. The microwaves rotating in the same direction as this precession direction efficiently supply energy to the ferromagnet and increase the precession amplitude. On the other hand, switching cannot be achieved by microwaves rotating opposite to the precession direction. This fact guarantees selective switching in microwave-assisted magnetization reversal.\(^16\)

In this letter, we study the magnetization dynamics excited by microwaves initially rotating opposite to the precession direction. Based on the energy balance equation, we analytically show that such microwaves can induce an unstable condition for the magnetization in equilibrium when the microwave frequency is time dependent. We propose a model of the system having a time-dependent microwave frequency to satisfy this analytical prediction. In the model, the microwaves initially rotate opposite to the precession direction for a certain period. After the initial magnetization state is destabilized, the microwaves change their rotating direction, and synchronize with the magnetization precession. Numerical simulation of the Landau-Lifshitz-Gilbert (LLG) equation confirms magnetization switching solely by such microwaves.

Figure 1 schematically shows the system under consideration. The magnetization \(\mathbf{m}\) precesses around the \(z\) axis, where the precession direction is determined by the precession torque, \(-\gamma \mathbf{m} \times \mathbf{H}\).

[Fig. 1. Schematic view of the system under consideration. The magnetization \(\mathbf{m}\) precesses around the \(z\) axis, where the precession direction is determined by the precession torque, \(-\gamma \mathbf{m} \times \mathbf{H}\).]

where \(\alpha\) is the Gilbert damping constant. We assume that \(\alpha\) is sufficiently small, i.e., \(1 + \alpha^2 \simeq 1\). Let us focus on the switching of a uniaxially magnetized ferromagnet. In this case, the magnetic field \(\mathbf{H}\) consists of a uniaxial anisotropy field along the easy (\(z\)) axis \(H_K\) and a microwave field rotating in the \(xy\)-plane as

\[
\mathbf{H} = H_{ac} \cos \psi \mathbf{e}_z + H_{ac} \sin \psi \mathbf{e}_y + H_K \mathbf{m},
\]

where \(H_{ac}\) and \(\psi\) are the amplitude and phase of the microwave field, respectively. The microwave frequency is defined as \(\nu \equiv (d\psi/dt)/(2\pi)\). In the absence of microwaves, the ferromagnet has two stable states at \(\mathbf{m} = \pm \mathbf{e}_z\). The precession direction of the magnetization due to the field torque, i.e., the first term on the right-hand side of Eq. (1), is a counterclockwise (clockwise) rotation with respect to the \(z\) axis when the initial magnetization starts from the positive (negative) \(z\)-direction. The rotation direction of the microwave field is counterclockwise (clockwise) for a positive (negative) frequency \(\nu\); see Fig. 1.

For further discussion, it is convenient to use a rotating frame \(x'y'z'\), in which the \(z'\)-axis is parallel to the \(z\)-axis and the \(x'\)-axis is always in the same direction as the microwave field.\(^{11}\) The LLG equation in the rotating frame

\[
\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H} - \alpha \gamma \mathbf{m} \times (\mathbf{m} \times \mathbf{H}), \tag{1}
\]
magnetic field in the rotating frame is a spin torque, where the unit vector along the magnetization in the rotating frame is denoted as $\mathbf{m}' = (m_{x}', m_{y}', m_{z}')$. The magnetic field in the rotating frame is

$$\mathbf{B} = H_{ac}\mathbf{e}_{z'} + \left(-\frac{1}{\gamma} \frac{d\psi}{dt} + H_{K}m_{z}'\right) \mathbf{e}_{z'}.$$  \hspace{1cm} (4)

As pointed out by Ref., Eq. (3) has a mathematical structure that is analogous to the LLG equation with a spin torque,\textsuperscript{18,19} where the last term of Eq. (3) corresponds to the spin torque term with a pinning layer pointing in the $z$-direction. Therefore, let us, for the moment, call the last term in Eq. (3) the spin torque for convention. This spin torque term moves the magnetization to the positive (negative) $z$-direction when the frequency is positive (negative). This means that the spin torque corresponding to the microwaves rotating opposite to the precession direction acts as an antidamping spin torque and tries to move the magnetization from equilibrium, $\mathbf{m} = \pm \mathbf{e}_{z}$. The phenomenon is due to the fact that such an antidamping spin torque does not favor a steady precession of the magnetization. However, the microwaves rotating opposite to the precession direction do not usually result in magnetization switching. This is because such microwaves at the same time makes the switched state energetically unstable, and the amplitude of the magnetization from equilibrium becomes relatively small.\textsuperscript{17}

We revisit this point by considering a time-dependent frequency. Note that, while experiments in past studies used microwaves with a constant frequency, the possibility is emerging to realize a time-dependent frequency by using an arbitrary wave generator or a spin torque oscillator (STO) coupled to the target ferromagnet.\textsuperscript{16} Several theoretical models have been proposed to show magnetization switching by microwaves with a time-dependent frequency.\textsuperscript{20–24} The previous theories are based on a resonant switching model,\textsuperscript{20} the variation method,\textsuperscript{21,22} and the autoresonance model.\textsuperscript{23} We recently proposed another type of resonant switching, in which the microwave frequency is always slightly different from the precession frequency.\textsuperscript{24} Macrospin and/or micromagnetic simulations confirmed switching of the magnetization by microwaves with a time-dependent frequency.\textsuperscript{20–25} These works, however, assume that the microwaves always rotate in the same direction as those of the magnetization precession. Below, let us consider the magnetization dynamics by microwaves rotating opposite to the precession direction with a time-dependent frequency, based on an extended model of our previous work.\textsuperscript{24}

To investigate the possibility of exciting the magnetization dynamics, it is convenient to study energy change of the system from the LLG equation.\textsuperscript{24} The energy density in the rotating frame is defined as $\mathcal{E} = -M \int d\mathbf{m}' \cdot \mathbf{B}$, where $M$ is the saturation magnetization. Then, from Eq. (3), the energy change, $d\mathcal{E}/dt = (d\mathbf{m}'/dt) \cdot (\partial \mathcal{E}/\partial \mathbf{m}') + (\partial \mathcal{E}/\partial t)$, is described as

$$\begin{align*}
\frac{1}{\gamma M} \frac{d\mathcal{E}}{dt} &= -\alpha \left( - \frac{1}{\gamma} \frac{d\psi}{dt} + H_{K}m_{z}' \right) H_{K}m_{z}' - \alpha H_{ac}^{2} \\
&+ \alpha \left[ H_{ac}m_{z}' + \left(-\frac{1}{\gamma} \frac{d\psi}{dt} + H_{K}m_{z}'\right) m_{z}' \right] \\
&\times \left( H_{ac}m_{z}' + H_{K}m_{z}'^{2} \right) \\
&+ \frac{1}{\gamma^{2}} \left( \frac{\partial d\psi}{\partial t} \right) m_{z}'.
\end{align*}$$  \hspace{1cm} (5)

The magnitude of the microwave field is usually much smaller than the uniaxial anisotropy field. Therefore, the dominant part of the energy change near the initial state, $\mathbf{m} \simeq \pm \mathbf{e}_{z}$, is

$$\begin{align*}
\frac{1}{\gamma M} \frac{d\mathcal{E}}{dt} &\sim -\alpha H_{ac}^{2} m_{z}'^{2} (1 - m_{z}'^{2}) \\
&+ \alpha H_{ac} \frac{1}{\gamma} \frac{d\psi}{dt} m_{z}' (1 - m_{z}'^{2}) \\
&+ \frac{1}{\gamma^{2}} \left( \frac{\partial d\psi}{\partial t} \right) m_{z}'.
\end{align*}$$  \hspace{1cm} (6)

Note that $d\mathcal{E}/dt$ should be positive to switch the magnetization. The first term is always negative because it comes from the damping torque. The second and third terms appear because of the presence of the microwaves. When the microwaves rotate in the same (opposite) direction as the precession direction, the second term is positive (negative) because $(d\psi/dt)m_{z}' \propto m_{z}' > 0$. Therefore, this term contributes to the increase (decrease) in the energy when the microwaves rotate in the same (opposite) direction as the magnetization precession. This is the common understanding in microwave-assisted magnetization reversal. On the other hand, the third term is finite when the microwave frequency is time dependent. This term can be positive even when the microwaves rotate opposite to the precession direction. An example can be found by considering the phase

$$\psi = c \gamma H_{K} \left( m_{z} + \epsilon \right) t,$$  \hspace{1cm} (7)

where $c$ and $\epsilon \in \mathbb{R}$ are assumed to be constant. The physical meanings of these parameters are discussed below. The microwave frequency is given by

$$\nu = \frac{c}{2\pi} \gamma H_{K} \left( m_{z} + \epsilon + \frac{d m_{z}}{dt} \right).$$  \hspace{1cm} (8)

We note that $f(t) = \gamma H_{K} m_{z}(t)/(2\pi)$ is the instantaneous frequency of the magnetization around the easy axis. The initial value of the microwave frequency, $\nu(0) = c \gamma H_{K} |m_{z}(0) + \epsilon|/(2\pi)$, has the opposite sign of the initial precession frequency of the magnetization, $f(0) = \gamma H_{K} m_{z}(0)/(2\pi)$, under the condition of a negative $c$ with $\epsilon > -1(<1)$ and $m_{z}(0) = (+(-)\mathbf{e}_{z})$. Thus, for the moment, let us assume that $|\epsilon| < 1$, for simplicity. Then, the microwaves initially rotate in the same (opposite) direction as (to) the precession for positive (negative) $c$, i.e., the sign of the parameter $c$ determines the
initial direction of the microwave rotation. One might consider that the model becomes simple by neglecting \( \epsilon \). As shown previously,\(^{24}\) however, the parameter \( \epsilon \) is necessary for deterministic switching. Then, Eq. (6) becomes

\[
\frac{1}{\gamma H_K^2} \frac{d\mathcal{E}}{dt} = -\alpha (1 - m_z^2) m_{z'} [(c - 1)m_{z'} + c \left( \epsilon + \frac{dm_{z'}}{dt} t \right)] + \frac{c}{\gamma H_K} \frac{dm_{z'}}{dt} m_{z'}.
\]

(9)

The term \((dm_{z'}/dt)m_{z'}\) is negative for an excitation of the magnetization from the equilibrium state, \( m = \pm e_z \), because \( m_z \) and \( dm_{z'}/dt \) have opposite signs. Then, the last term, which is proportional to \( c(dm_{z'}/dt)m_{z'} \), as well as \( d\mathcal{E}/dt \), can be positive for a negative \( c \). Note that Eq. (9) is valid only near the initial state. Therefore, this result implies the possibility of destabilizing the magnetization by microwaves initially rotating opposite to the precession direction. We also emphasize that this conclusion is obtained only when the microwave frequency explicitly depends on time. If the microwave frequency is constant, the last term in Eq. (9) does not appear, and therefore, \( d\mathcal{E}/dt \) becomes negative for microwaves rotating opposite to the precession direction.

The model of the phase, Eq. (7), as well as the microwave frequency, Eq. (8), was referenced from our previous work corresponding to \( c = 1 \).\(^{24}\) The purpose of the previous work was to achieve microwave-assisted magnetization reversal by introducing a difference between the instant precession frequency of the magnetization, \( \gamma H_K m_z(t)/(2\pi) \), and the microwave frequency \( \nu \). We showed in that study that the magnetization climbs up the energy landscape to synchronize the precession frequency with the microwave frequency and finally switches its direction to the other equilibrium. The parameter \( c \) characterizes the difference between the instant precession frequency of the magnetization and the microwave frequency. This model originated from the recent observation of magnetization switching solely by microwaves in micromagnetic simulation,\(^{25}\) as well as the experimental observation of the synchronization between the target ferromagnet and an STO.\(^{16}\) As pointed out in Ref.\(^{24}\) the term proportional to \( (dm_{z'}/dt)t \) in Eq. (8) characterizing the difference between the precession frequency and the microwave frequency is also necessary for switching. The present model introduces another parameter \( c \), which controls the sign and amplitude of the microwave frequency. The microwaves with positive (negative) \( c \) and \(|c| < 1 \) initially rotate in same (opposite) direction as (to) the magnetization precession, as mentioned above. In this sense, the parameter \( c \) determines the rotation direction of the microwaves. For example, in the system where the target ferromagnet and STO are coupled, a positive (negative) \( c \) means that the magnetizations in the target ferromagnet and the free layer in the STO initially precess in same (opposite) directions. It should be noted, however, that the microwave frequency in the present model might change its sign during precession because the terms \( m_z \) and \( dm_{z'}/dt \) in Eq. (8) have opposite signs.

Summarizing the above discussions, Eq. (9) implies the possibility of destabilizing the magnetization at an equilibrium by microwaves rotating opposite to the precession direction and having a time-dependent frequency. As an example, we consider the phase of the microwaves given by Eq. (7). Two parameters, \( c \) and \( \epsilon \), introduced in Eq. (7) or Eq. (8), characterize the initial rotating direction of the microwaves and the phase difference between the instant precession frequency of the magnetization and the microwave frequency, respectively. In a coupled system between a target ferromagnet and an STO, not only the phase \( \psi \) but also the amplitude \( H_{ac} \) of the microwave field might depend on time. A way to describe such a system is to extend \( c \) and/or \( \epsilon \) to a complex number, \( c, \epsilon \in \mathbb{C} \).

We performed numerical simulations of Eq. (1) to confirm the above idea. The values of the parameters are taken from typical experiments and numerical simulations,\(^{4,7,12,14}\) as \( M = 1000 \) emu/c.c., \( H_K = 7.5 \) kOe, \( H_{ac} = 450 \) Oe, \( \gamma = 1.764 \times 10^7 \) rad/(Oe·s), and \( \alpha = 0.01 \). The initial state is \( m(0) = +e_z \). Note that the precession frequency of the magnetization, \( \gamma H_K m_z/(2\pi) \), is positive during the period from the initial state to the state where the magnetization reaches the \( xy \)-plane, in which \( m_z > 0 \). Figure 2(a) shows the time evolutions of \( m_z \), the instant precession frequency \( f = \gamma H_K m_z/(2\pi) \), and the microwave frequency \( \nu \) for \((c, \epsilon) = (-1, 0)\). The microwave frequency, Eq. (8), initially takes a negative value, meaning that the magnetization and microwaves rotate in opposite directions. Nevertheless, the magnetization moves away from the initial state. Then, the microwave frequency rapidly changes to a positive value and almost becomes synchronous with the precession frequency. The magnetization finally arrives at the \( xy \)-plane, \( m_z = 0 \), and stops its dynamics because all torques are zero on this plane. For comparison, the time evolutions of \( m_z \) and \( \nu \) for \((c, \epsilon) = (1, 0)\) are shown in Fig. 2(b). In this case, the microwaves always rotate in the same direction as the magnetization precession, i.e., \( \nu > 0 \). We should emphasize here that the magnetization finally saturates at a position above the \( xy \)-plane (\( m_z \simeq 0.6 \) in this case). This result implies that the present model \((c = -1)\) is more efficient of destabilizing the magnetization from equilibrium than our previous proposal \((c = 1)\)\(^{24}\) because microwaves rotating opposite to the precession direction do not stabilize the
precession around the equilibrium.

In practical application such as a magnetic recording, the value of $m_z$ after turning off the microwaves is also important. Therefore, we also perform numerical simulations in which the microwaves are applied to the ferrimagnet from $t = 0$ to $t = 5$ ns, and the relaxation dynamics after turning off the microwaves are calculated from $t = 5$ to $t = 10$ ns. Figures 3(a) and 3(b) show examples of such dynamics, where the value of the parameter $\epsilon$ is (a) 0 and (b) 0.1. For $\epsilon = 0$, the values of $m_z$ saturate above the $xy$-plane for both $c = \pm 1$. Therefore, after turning off the microwaves, the magnetization returns to the initial equilibrium state. When $\epsilon = 0.1$, the magnetization moves close to the $xy$-plane, and for $c = -1$, the magnetization reaches below the $xy$-plane, and therefore, moves to the other equilibrium state after turning off the microwaves. On the other hand, for $c = 1$, the magnetization reaches above the $xy$-plane. We note that this result does not contradict our previous work\(^{(24)}\) in which magnetization switching was observed for $(c, \epsilon) = (1, 0.1)$. The difference between the present and previous works is the time over which the microwaves are applied, which is 5 ns in this study while it was 50 ns in the previous work. In other words, to achieve switching for $c = 1$, the microwaves should be applied for a relatively long time compared with the case of $c = -1$. From the perspective of switching performance, the present model ($c < 0$) will be an attractive method for fast switching. Figures 3(c) and 3(d) summarize the values of $m_z$ in the presence of the microwaves, $m_z(t = 5$ ns), and after turning off the microwaves, $m_z(t = 10$ ns). As shown, magnetization switching is achieved for a wide range of $\epsilon$ for $c = -1$, compared with the case of $c = 1$.

It is theoretically interesting to investigate the switching possibility for wider ranges of $c$ and $\epsilon$. In this case, however, a negative $c$ no longer guarantees that the microwave initially rotates opposite to the precession for $|\epsilon| > 1$, as mentioned above. Figures 4(a) and 4(b) summarize the values of $m_z$ at $t = 5$ ns and (b) $t = 10$ ns. The initial state is $\mathbf{m}(0) = +\mathbf{e}_z$.

In conclusion, we showed that microwaves initially rotating opposite to the precession direction of the magnetization destabilize the magnetization at equilibrium when the microwave frequencies are time dependent. This argument was analytically deduced from an energy balance equation. We proposed a model of the system having a time-dependent microwave frequency with two parameters, $c$ and $\epsilon$ to test the possibility of switching by such microwaves. The parameters $c$ and $\epsilon$ characterize the rotation direction of the microwaves near the initial state and the difference between the instant precession frequency of the magnetization and the microwave frequency, respectively. We confirmed magnetization switching solely by microwaves rotating initially opposite to the precession direction by numerical simulation. We also showed that the use of such microwaves has the possibility of realizing fast switching compared with microwaves always rotating in the same direction.

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