

Magnetization reversal through synchronization with a microwave

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Based on the Landau-Lifshitz-Gilbert equation, it can be shown that a circularly polarized microwave can reverse the magnetization of a Stoner particle through synchronization. In comparison with magnetization reversal induced by a static magnetic field, it can be shown that when a proper microwave frequency is used the minimal switching field is much smaller than that of precessional magnetization reversal. A microwave needs only to overcome the energy dissipation of a Stoner particle in order to reverse magnetization, unlike the conventional method with a static magnetic field where the switching field must be of the order of magnetic anisotropy.

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INTRODUCTION

Magnetization reversal of single-domain magnetic nanoparticles (Stoner particles)¹ is of significant interest in magnetic data storage and spintronics. Finding an effective way to switch magnetization from one state to another depends on our basic understanding of magnetization dynamics. Magnetization can be manipulated by laser,² a polarized electric current,^{3,4} or a magnetic field.⁵ An important issue in magnetization reversal is the minimal switching field. Magnetization reversal using a static magnetic field⁵⁻⁸ or polarized electric current^{3,4} has received close attention in recent years, but there has been little investigation on microwave-induced magnetization reversal. Thirion *et al.*⁹ made probably the first attempt in this direction. It was shown that a dramatic reduction of the minimal switching field is possible by applying a small radio-frequency (rf) field pulse (the decrease in the static field is much larger than the amplitude of the rf field). Some numerical investigations in this direction were also given in Ref. 10. In this paper, it is shown that a circularly polarized microwave on its own can induce magnetization reversal. The minimal switching field depends on the microwave frequency. It can be shown that the minimal switching field is at a minimum at an optimal frequency. This optimal frequency is near the natural precession frequency at which the particle experiences the largest dissipation. At this optimal frequency, the switching field strength can be much smaller than the so-called Stoner-Wohlfarth (SW) limit¹¹ and precessional magnetization switching field⁵⁻⁷ for a static magnetic field. Far from the optimal frequency, the switching field can be larger than the SW limit.

The minimal switching field was first studied by Stoner and Wohlfarth.¹¹ The SW limit is the field at which the energy minimum around the initial state is destroyed and the target state is the only minimum,⁵⁻⁸ as illustrated in Figs. 1(a) and 1(b). In the absence of magnetic fields: A and B are the two minima, separated by a potential barrier ΔE , are along the easy axis of a magnetic particle. At the SW limit, the original minimum near the initial state A disappears [Fig. 1(b)], and the particle will end up at its unique minimum near the target state B . Recent theoretical and experimental studies⁵⁻⁷ have shown that the minimal switching field could be smaller than the SW limit. The reason has been

explained earlier.⁸ As illustrated in Fig. 1(c), magnetization reversal can occur even when the minimum around A exists. The reversal can happen as long as the particle energy at A is higher than that at the saddle point SP , and the particle can pass through SP under its own dynamics. It can be shown that the minimal switching field is of the order of the potential barrier ΔE .⁸

FUNDAMENTAL DIFFERENCES BETWEEN TIME-INDEPENDENT AND TIME-DEPENDENT FIELDS

The microwave-induced magnetization reversal is fundamentally different from that of a static magnetic field, because a static field is not an energy source while a microwave can be. This can be seen from the dynamic equation governing the evolution of a single-domain magnetic nanoparticle. For a particle with a magnetization of $\vec{M} = \vec{m}M_s$, \vec{m} satisfies the Landau-Lifshitz-Gilbert (LLG) equation^{8,12}

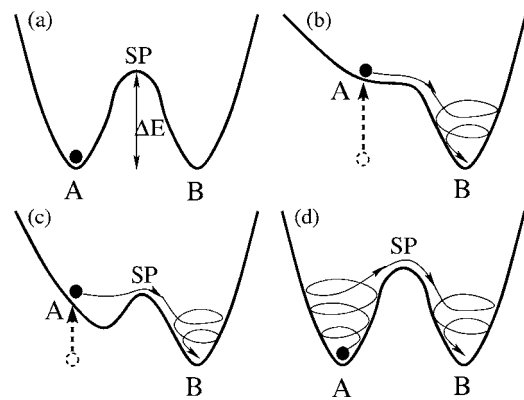


FIG. 1. Energy surface of a uniaxial magnetic particle in various schemes. SP denotes the saddle point between two minima. (a) In the absence of magnetic fields: A and B are the two minima, separated by a potential barrier ΔE . (b) At the SW limit: Target state B is the only minimum. (c) Precessional magnetization reversal: The particle energy at A is higher than that at SP so that it can pass through SP under its own dynamics. (d) New strategy: The system synchronizes its motion with a microwave, and climbs over the potential barrier to reverse its magnetization.

$$(1 + \alpha^2) \frac{d\vec{m}}{dt} = -\vec{m} \times \vec{h}_t - \alpha \vec{m} \times (\vec{m} \times \vec{h}_t), \quad (1)$$

where M_s is the saturated magnetization of the particle, and α is a dimensionless damping constant. The total field, measured in unit of M_s , comes from an applied magnetic field \vec{h} and the internal effective field \vec{h}_i due to the magnetic anisotropy $w(\vec{m}, \vec{h})$, $\vec{h}_i = -\nabla_{\vec{m}} w(\vec{m}, \vec{h}) = \vec{h}_i + \vec{h}$. In Eq. (1), time t is in unit of $(|\gamma| M_s)^{-1}$ with $|\gamma| = 2.21 \times 10^5 (\text{rad/s}) / (\text{A/m})$ being the gyromagnetic ratio. From Eq. (1), the energy change rate for the particle can be obtained,¹³

$$\frac{dw}{dt} = -\vec{m} \cdot \dot{\vec{h}} - \frac{\alpha}{1 + \alpha^2} |\vec{m} \times \vec{h}_t|^2. \quad (2)$$

The second term due to the damping is always negative, while the first term due to the external magnetic field can be either positive or negative if the field varies with time. Thus, a time-dependent magnetic field can be both an energy source and energy sink.

NEW STRATEGY

Having explained that a microwave can be an energy source, the *synchronization* phenomenon of nonlinear dynamic systems¹⁴ can be used to reverse the magnetization of a Stoner particle by shining the particle with only a circularly polarized microwave. If the propagating direction of the microwave is along the particle's easy axis (the magnetic field rotates around the easy axis with the microwave frequency), the particle's magnetization in a synchronized motion precesses around the axis with the microwave frequency. As illustrated in Fig. 1(d), the magnetization starting from its initial minimum A obtains energy from the microwave and eventually reaches its synchronized state. If the synchronized state is over the saddle point SP and on the side of minimum B , the magnetization reversal is realized when the microwave radiation is turned off because magnetization will end up at minimum B through the usual ringing effect.⁵ It is known that a nonlinear dynamic system under an external periodic field may undergo a nonperiodic motion other than synchronization.¹⁴ In general, the reversal criterion is: The magnetization is reversed if the system can cross the saddle point SP in Fig. 1.

To demonstrate the feasibility of the new strategy, a uniaxial magnetic anisotropy is considered,

$$w(\vec{m}, \vec{h} = 0) = -km_x^2, \quad (3)$$

where $k > 0$ measures the anisotropy strength. Without losing the generality, k [used as a scale for the field strength according to Eq. (1)] shall be set to 1. The easy axis is chosen to be along the x axis rather than the z axis because the north and south poles are singular in spherical coordinates, and it is more convenient to locate the minima A and B (Fig. 1) away from the singularities.

MULTIPLE SYNCHRONIZATION SOLUTIONS

Under a circularly polarized microwave of amplitude h_0 and frequency ω ,

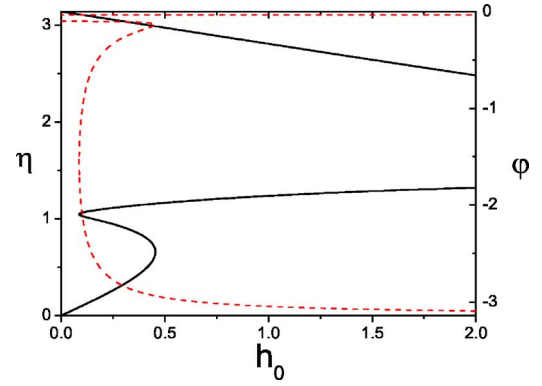


FIG. 2. (Color online) Graphic demonstration of multiple synchronization solutions. The solid lines are from Eq. (6) and the dashed lines are from Eq. (7). The graph is plotted at $\alpha=0.1$ and $\omega=1$.

$$\vec{h}(t) = h_0 [\cos(\omega t) \hat{y} + \sin(\omega t) \hat{z}], \quad (4)$$

and the synchronized motion is

$$\vec{m}(t) = \cos \eta \hat{x} + \sin \eta [\cos(\omega t + \varphi) \hat{y} + \sin(\omega t + \varphi) \hat{z}], \quad (5)$$

where η (a constant of motion) is the precessional angle between \vec{m} and the x axis. φ is the locking phase in the synchronized motion. By substituting Eqs. (3)–(5) into Eq. (1), η and φ satisfy

$$\sin \eta \sqrt{\alpha^2 \omega^2 + (2 - \omega / \cos \eta)^2} = h_0, \quad (6)$$

$$\sin \varphi = -\alpha \omega \sin \eta / h_0, \quad (7)$$

where $\eta \in [0, \pi]$. For fixed (h_0, ω, α) , η and φ may have multiple solutions. As illustrated in Fig. 2, the solutions of η (solid lines) are plotted as a function of h_0 for $\omega=1$ and $\alpha=0.1$. The dashed lines denote the corresponding φ . Multiple solutions of η, φ are evident. For example, there are four solutions of η, φ when $h_0 \in [0.09, 0.45]$. Numerically, it can be shown that two solutions at around $\eta=1$ (in between) are unstable, while the other two near $\eta=0, \pi$ are stable. Thus, the system shall eventually end up at one of the two stable solutions. Which one the system will choose depends on the initial condition. For a given initial condition [$\vec{m}(0)=\hat{x}$ in this study], the system picks the solution near $\eta=\pi$ when h_0 is larger than a critical value called the minimal switching field. According to our reversal criterion, the magnetization is reversed through synchronization.

NUMERICAL VERIFICATION OF SYNCHRONIZED AND NONSYNCHRONIZED MOTION

A nonlinear dynamic system under an external periodic field may undergo motion other than synchronized. Unfortunately, a nonsynchronized motion is, in general, hard to define analytically. Usually, reliance must be placed on the numerical method. In terms of the LLG equation under a circularly polarized microwave of Eq. (4), it is straightforward⁸ to calculate numerically $\vec{m}(t)$ starting from $\vec{m}(0)=\hat{x}$. The upper inset of Fig. 3 is the trajectory of $\vec{m}(t)$

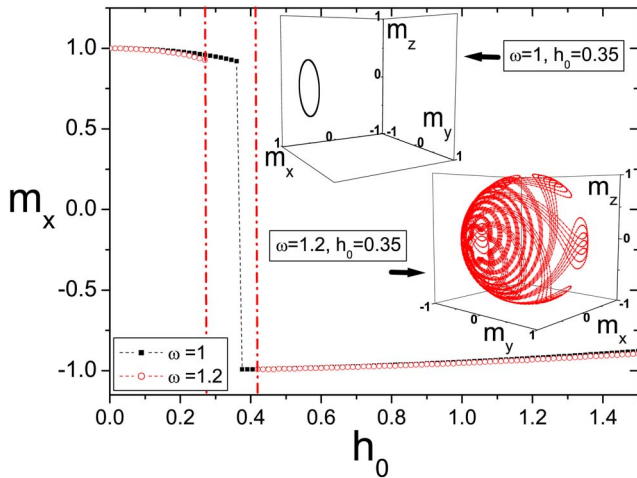


FIG. 3. (Color online) m_x of synchronized motion vs h_0 for $\alpha=0.1$ and $\omega=1$ (filled squares); 1.2 (open circles). Nonsynchronized motion when $h_0 \in [0.27, 0.42]$ (between two dash-dotted lines) is found for $\omega=1.2$. Upper inset: Long time trajectory of $\vec{m}(t)$ for $\omega=1$ and $h_0=0.35$. Lower inset: Long time trajectory of $\vec{m}(t)$ for $\omega=1.2$ and $h_0=0.35$.

after long time in $m_x m_y m_z$ space for $h_0=0.35$, $\omega=1$, and $\alpha=0.1$. A simple closed loop in a plane parallel to the yz plane indicates that this is a synchronized motion. Alternatively, the lower right inset of Fig. 3 is the long time trajectory of $\vec{m}(t)$ for $h_0=0.35$, $\omega=1.2$, and $\alpha=0.1$. Its motion is very complicated, corresponding to a nonsynchronized motion. It is found that whether the motion is synchronized or not is sensitive to the microwave frequency. For example, all motions for $\omega=1$ are synchronized, while both synchronized and nonsynchronized motions are possible for $\omega=1.2$. The motion is nonsynchronized for h_0 in the range of $[0.27, 0.42]$, while it is synchronized for other values of h_0 . Figure 3 is m_x of synchronized motions as a function of h_0 for $\omega=1$ and 1.2.

OPTIMAL MICROWAVE FREQUENCY

Using the reversal criterion given earlier, it can be shown from Fig. 3 that the minimal switching field h_c is about 0.375 for $\omega=1$ because m_x in the synchronized motion is negative when $h_0 > h_c$. For $\omega=1.2$, the minimal switching field takes a value at which the magnetization undergoes a nonsynchronized motion. Numerically, it can be shown that \vec{m} crosses the yz plane when $h_0 \geq 0.285$. Thus, the minimal switching field is determined as $h_c=0.285$ for $\omega=1.2$. The reason that the value of the minimal switching field is so sensitive to the microwave frequency is because a switching field, as illustrated in Fig. 1(d), needs to overcome the dissipation which is related to the motion of the magnetization (see the LLG equation). To reveal the frequency dependence of the minimal switching field, Fig. 4 shows the minimal switching field h_c vs the microwave frequency ω for various $\alpha=0, 0.001, 0.1, 1, \text{ and } 1.5$. $\omega=0$ corresponds to the case of a static field along the y axis. The curve of $\alpha=0$ intersects the h_c axis at $h_c=1$, which agrees with the exact minimal switching field $h_c=1$.⁸ The intersections of all other curves of $\alpha \neq 0$ are the

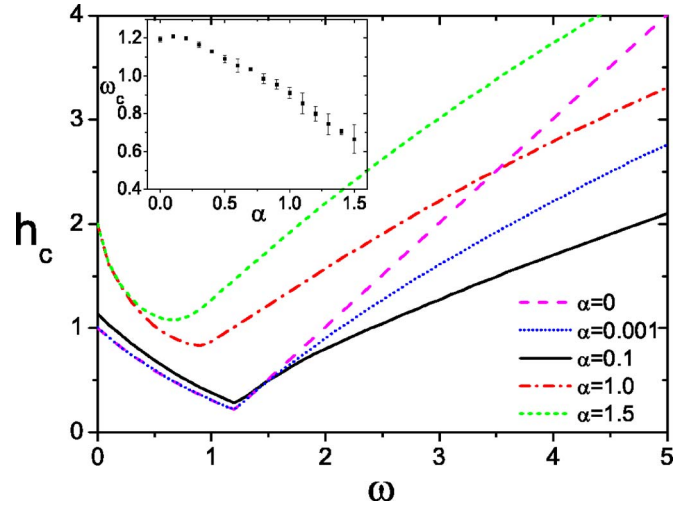


FIG. 4. (Color online) The minimal switching field h_c vs ω for various damping constants $\alpha=0, 0.001, 0.1, 1, \text{ and } 1.5$. Inset: The optimal frequency ω_c vs α .

same as those with a static field.^{5,8} When $\alpha \geq 1$, it becomes the SW limit $h_c=2$. For a given α , Fig. 4 shows the existence of an optimal microwave frequency, ω_c , at which the minimal switching field is the smallest. Far from the optimal frequency, the minimal switching field can be larger than the SW limit. The inset of Fig. 4 is ω_c vs α . The optimal frequency is near the natural precessional frequency at which the dissipation is a maximum.

SWITCHING FIELD AS A FUNCTION OF DISSIPATION

From the above discussions, it can be seen that the minimal switching field is a minimum at the optimal frequency ω_c . The square symbols in Fig. 5 are the minimal switching

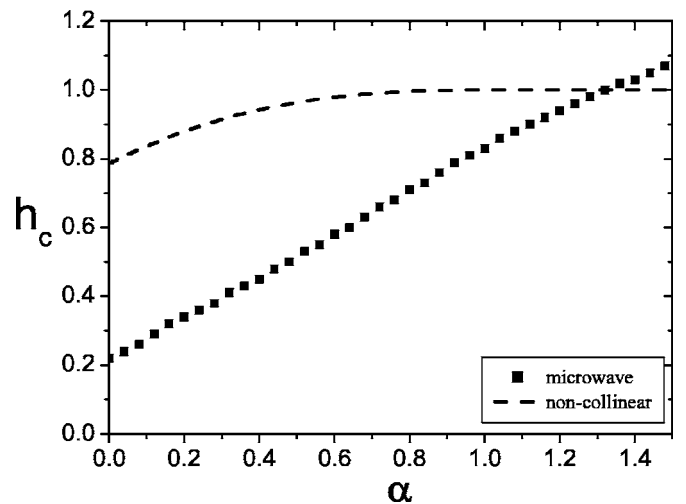


FIG. 5. h_c vs α for the uniaxial model of Eq. (3) under different reversal schemes. Square symbols are the numerical results of h_c at the optimal frequency in the present strategy with a circularly polarized microwave. The dashed line is h_c under a noncollinear static field of 135° to the easy axis. It saturates to the SW limit beyond $\alpha=1$ (Ref. 8).

fields at ω_c with different damping constant α for the uniaxial model of Eq. (3). They follow approximately the line of $h_c \approx 0.23 + 0.58\alpha$. This approximate linear relation is related to the fact that the damping (field) is proportional to α . For comparisons, the minimal switching fields of a precessional magnetization reversal under a static magnetic field, which saturates to the SW limit beyond $\alpha=1$, is also plotted in Fig. 5. It can be seen that for small damping, the smallest (at the optimal frequency) minimal switching field can be much smaller than that in the precessional magnetization reversal. For large damping, the switching field can be larger than the SW limit.

DISCUSSION AND CONCLUSIONS

It is important to compare the present strategy with other strategies involving time-dependent fields. Firstly, the current scheme is fundamentally different from that in the experiment of Thirion *et al.*⁹ in several aspects. (i) A circularly polarized microwave of fixed frequencies is the only switching field in the new scheme, while in Ref. 9, a linear polarized rf field is used as an additional external field to reduce the main static switching magnetic field. (ii) For a Co particle of $H_i=10^5$ A/m,⁶ the optimal frequency is about order of 10 GHz rather than order of 1 GHz employed in Ref. 9. At a few GHz, Fig. 4 shows that the switching field would be too large to have any advantage over a static field. The current scheme is also very different from that in Ref. 13 in

many aspects. (i) The time-dependent field in Ref. 13 is used as a ratchet that should be adjusted with the motion of magnetization. In contrast, the present scheme is based on the synchronization phenomenon in nonlinear dynamics such that a circularly polarized microwave of fixed frequencies is used and the magnetization motion is synchronized with the microwave in the reversal process. (ii) The switching field in Ref. 13 is in general nonmonochromatic and very complicated, requiring a precise control of time-dependent polarization. Thus, it would be a great challenge to generate such a field. Alternatively, the current scheme is much easier to implement and it could be technologically important.

In conclusion, a circularly polarized, microwave-induced magnetization reversal is proposed. The proposal is based on the facts that a microwave can constantly supply energy to a Stoner particle, and the magnetization motion can be synchronized with the microwave. It can be demonstrated that a Stoner particle under the radiation of a circularly polarized microwave can indeed move out of its initial minimum and climb over the potential barrier. The switching field at the optimal microwave frequency will be much smaller than the SW limit and that of the precessional magnetization reversal for small damping.

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