Magnetization reversal in the anisotropy-dominated regime using time-dependent magnetic fields

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The authors study magnetization reversal using various rf magnetic pulses. The authors show numerically that switching is possible with simple sinusoidal pulses; however, the optimum approach is to use a frequency-swept (chirped) rf magnetic pulse, the shape of which can be derived analytically. Switching times of the order of nanoseconds can be achieved with relatively small rf fields, independent of the anisotropy's strength.
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Among the underlying physics issues associated with magnetic memory devices, perhaps the most subtle process is that by which the magnetization direction is reversed (switched).[1] As far as we are aware, Thirion *et al.*[2] were the first to show, experimentally, that in the presence of magnetic anisotropy, reversing the magnetic field while simultaneously applying a rf field at right angles to the applied dc field can significantly lower the threshold for switching. These authors also concluded that the most effective frequency for small-amplitude oscillations corresponded to the uniform-mode ferromagnetic resonance (fmr) frequency. Theoretical analysis of a similar case was given in works by Bertotti and co-workers.[3,4]

Prior to the work cited, reversal via rf fields had been studied theoretically.[5,6] Bauer *et al.*[7] showed that *in the absence* of a constant, H_0, field, a dc pulse (one for which the field remains positive throughout the pulse) can produce switching in materials with uniaxial anisotropy. However, the switching times reported were quite long, of the order of 500 ns for typical conditions. In the present letter we explore constant-frequency as well as frequency-swept (chirped) rf pulse profiles in order to better optimize the switching time.

We identify two different regimes in which to consider magnetization reversal via rf pulses, depending on whether H_0 is greater than or less than the effective anisotropy field. In the first case one might excite large-amplitude uniform precession at the fmr frequency, analogous to what is done in nuclear magnetic resonance experiments.[8] This approach has not been particularly effective in ferromagnets due the onset of the so-called *Suhl instability*[9] which arises from the nonlinear excitation of nonuniform spin modes; this phenomenon ultimately leads to spatial decoherence and, for sufficiently long times and high values of the applied rf field, chaos.[10] However, as shown in Ref. 11, this instability can be greatly suppressed by choosing favorable values of the H_0 field and sample size. Furthermore, in most cases, this instability becomes irrelevant for objects smaller than 300 nm.

Most magnetic memories utilize, in one way or another, magnetic anisotropy to store information. The application of a rf pulse can lower the dc field required to induce switching; however, in this letter we consider the case when the switching is accomplished with rf fields alone.

Here we will limit our numerical studies to the case where $H_0=0$. As material parameters we choose a bismuth-substituted yttrium iron garnet sphere having a saturation magnetization $M_s=120$ Oe and a damping coefficient $\beta=0.001$; the anisotropy coefficient $K=7.3\times 10^4$ ergs/cm corresponds to an effective anisotropy field of 608 Oe or, equivalently, a small-amplitude precession frequency $\omega_K/2\pi=1.69$ GHz. We will assume that the sphere can be approximated by a *single spin*; based on our simulations with ensembles, this turns out to be reasonably accurate if the diameter is less than 300 nm. We further assume that the z axis is the easy axis with the magnetization initially along the positive direction.

At $t=0$ we apply a circularly polarized rf field in the x-y plane having the forms

$$H_x^{\mathrm{rf}}=H_1\cos(\phi(t)),$$

$$H_y^{\mathrm{rf}}=H_1\sin(\phi(t)), \tag{1}$$

where in our simulations the amplitude H_1 will be constant during the application of the pulse and zero otherwise. For a constant applied frequency $\phi(t)=\phi_0+\omega t$; for a swept pulse we define the *instantaneous* frequency as $\omega(t)=d\phi/dt$. We then solve the Landau-Lifshitz[12] equation

$$\frac{d\mathbf{m}}{dt}=-\gamma\mathbf{m}\times\mathbf{h}^{\mathrm{total}}-\frac{\beta\gamma}{M_s}\mathbf{m}\times(\mathbf{m}\times\mathbf{h}^{\mathrm{total}}) \tag{2}$$

using a fourth order Runge-Kutta algorithm; here $\mathbf{m}$ is the magnetization and $\mathbf{h}^{\mathrm{total}}$ is the sum of the applied rf field and the anisotropy field, γ is a gyromagnetic coefficient, and β is a damping parameter.

We first examine the case of a constant applied frequency and ask which frequencies produce the maximal rotation of the magnetization. Figure 1 shows M_z as a function of $\omega/2\pi$ for two different values of rf field, −50 and 100 Oe. For our single-spin model, switching will occur following a rotation by an angle greater than $\pi/2$; the moment must then subsequently relax to the negative z direction. Note that rela-

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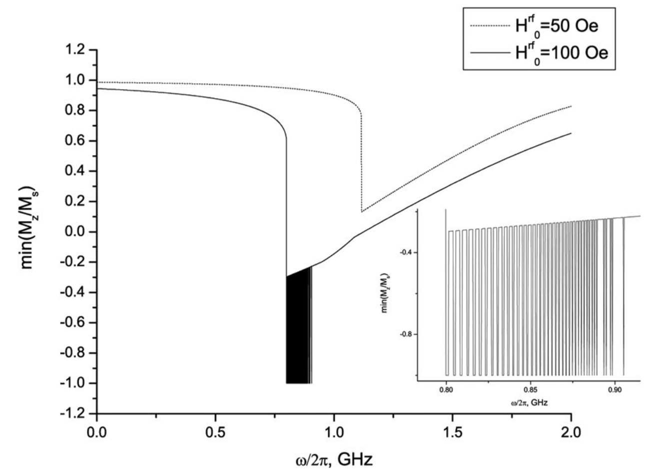

FIG. 1. Minimal value of M_z as a function of frequency for two values of the rf field $H_1=100$ Oe and $H_1=50$ Oe.

tively high rf fields are required to produce switching. On the other hand rotation induced by a dc pulse applied perpendicular to the z axis requires still larger fields.

We note that the frequency associated with the anisotropy field, $\omega_K(\theta)$, is *angle dependent*, θ being the angle between the spin and the anisotropy axis (the z axis), and going to zero at $\theta=\pi/2$. For this reason we find that $\omega_K(0)$ is not the optimal frequency for switching; the optimal frequency turns out to be about half of $\omega_K(0)$. Moreover switching is possible only within a set of narrow frequency ranges. Switching with a constant frequency has another disadvantage—while it takes only a few nanoseconds for M_z to become negative, full switching ($\theta=\pi$) takes about 500 ns to complete, the time dependence of M_z being mostly oscillatory (implying the necessity of a significant time separation between "writing" and reliably reading or rewriting the magnetic state). Because of this the optimal switching strategy is to use a short rf pulse with a carefully chosen frequency and width; one can then reach values of M_z/M_s as low as -0.35 before the system starts to oscillate back towards the positive values of M_z. At this point we turn off the rf field and wait for the damping to relax the system towards $M_z/M_s=-1$. Unfortunately it can be shown that M_z remains positive with an exception of a few narrow time regions, which forces the pulses lengths to be very precise.

As noted above, $\omega_K(\theta)$ is angle dependent and, since $\theta=\theta(t)$, this frequency is consequently time dependent. Because of this, it is natural to apply a pulse for which the frequency is *time dependent*, a so-called *chirped* pulse, so that the rf field is always in resonance with the sample. Initially we attempted to numerically calculate the frequency $\omega(t)$ which yields the fastest possible switching, and in parallel, using spectral, conjugate gradient, and Monte Carlo methods. The results of this calculation are presented in Fig. 2. However, it was then realized that when the damping is small this optimal switching can be expressed as an analytical solution of the Landau-Lifshitz equation (in the most general case a dc field H_0 is also applied along the z axis; however, its presence is unnecessary):

$$\dot{M}_x=-\gamma\left(M_y\left(K\frac{M_z}{M_s^2}+H_0\right)-M_zH_1\sin(\varphi(t))\right),$$

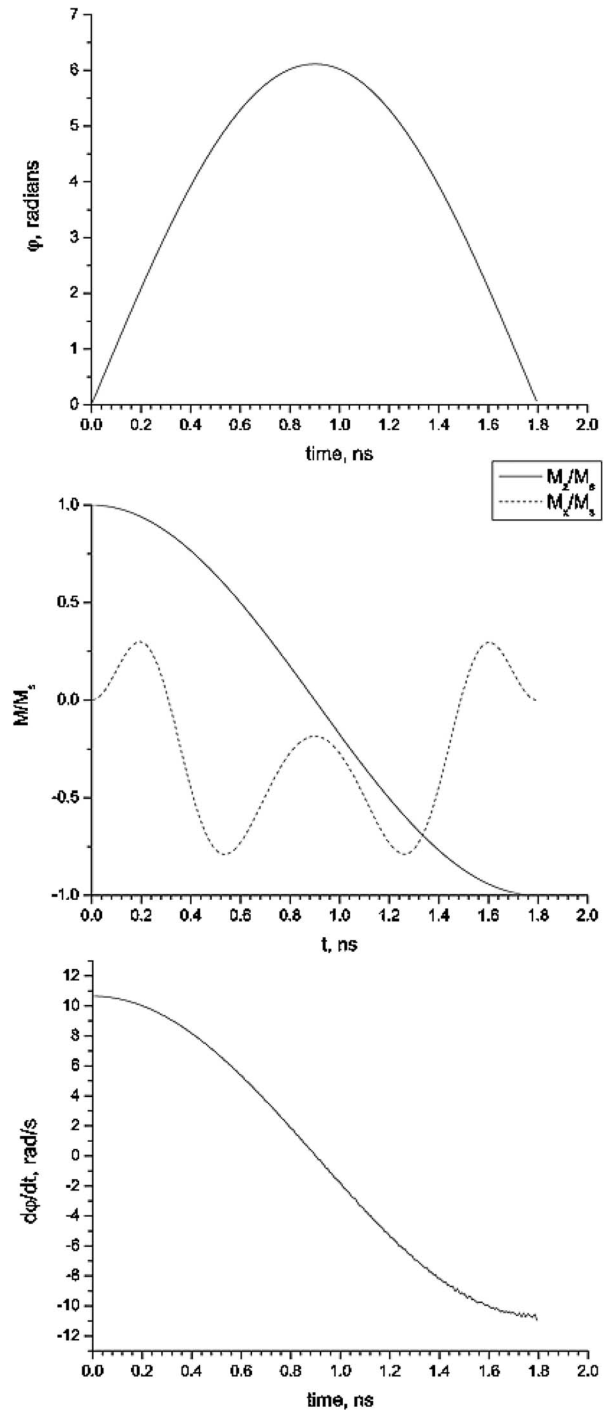

FIG. 2. Time when M_z is equal to 0 as a function of frequency for rf field $H_1=100$ Oe.

$$\dot{M}_y=-\gamma\left(M_zH_1\cos(\varphi(t))-M_x\left(K\frac{M_z}{M_s^2}+H_0\right)\right),$$

$$\dot{M}_z=-\gamma(M_xH_1\sin(\varphi(t))-M_yH_1\cos(\varphi(t))); \tag{3}$$

in order for switching to be optimal, $\omega(t)$ should always be equal to the resonant frequency:

$$\omega(t)\equiv\frac{d\varphi(t)}{dt}=\gamma\frac{K}{M_s^2}M_z+\gamma H_0. \tag{4}$$

Integrating Eq. (4) we can obtain the expression for $\varphi(t)$ (the angle that the rf field forms with the x axis), and thereby solve Eq. (3):

$$M_x = M_s \sin(\gamma H_1 t)\sin(\varphi(t)),$$

$$M_y = - M_s \sin(\gamma H_1 t)\cos(\varphi(t)),$$

$$M_z = M_s \cos(\gamma H_1 t), \tag{5}$$

$$\varphi(t) = K\frac{\sin(\gamma H_1 t)}{H_1 M_s} + \gamma H_0 t. \tag{6}$$

As can be seen in Fig. 2, $\omega(t)$ always corresponds to the frequency $\omega_K(\theta)$; initially it is equal to $\omega_K(0)$, then goes through zero when $M_z(t)=0$, and is equal to $-\omega_K(0)$ when $M_z(t)=-M_s$.

The stability of this chirped-frequency switching was tested by applying a random, uniformly distributed noise to $\varphi(t)$: the switching still occurs for values of the noise as high as 25% of φ.

The presence of damping fixes minimal H_1 that will produce switching. Since the energy supplied by the rf field must sustain the motion despite the absorption due to the damping for all values of $\theta(t)$, it can be shown that

$$H_1(\theta) > \beta \sin(\theta)\left(H_0 + \frac{K}{M_s}\cos(\theta)\right),$$

$$H_0 = 0 \Rightarrow \max(H_1) > \frac{1}{2}\frac{K}{M_s}\beta. \tag{7}$$

As one can see the value of H_1 needed for magnetization reversal is relatively small for most situations.

If for technical reasons we are constrained to rf fields applied only along one of the coordinate axes (for example, the x axis), we found numerically that a series of square (flattopped) pulses of equal magnitude, alternating sign, and varying width produces nearly optimal switching; such a wave form might be synthesized digitally in practice. The associated pulse widths are chosen so as to maximize the decrease in M_z. The rate of change of M_z due to the applied rf field is given by

$$\frac{dM_z}{dt} = \gamma M_y H_x^{\mathrm{rf}}; \tag{8}$$

hence if we wish to minimize this term with the chosen wave form, the sign of H_x^{rf} should be opposite to that of M_y. In Fig. 3 we present the resulting pulse sequence and the behavior of M_z/M_s versus time for the case where the amplitude of rf field $H_1=25$ Oe.

In conclusion, we have established that efficient switching of the magnetization direction of a spin precessing under the joint influence of an anisotropy field and an external rf field can be achieved in the absence of an applied dc field. We find the following behaviors:

(1) The optimal frequency for switching with a *nonchirped* rf pulse is approximately half the small-amplitude precession frequency associated with the anisotropy energy; switching is possible only for rf pulses with amplitudes above some threshold value. Due to the oscillatory nature of such switching, the pulse length must be chosen precisely, terminating it before the system goes back to positive value of M_z; the remainder of the switching occurs via damping.

(2) Switching with a chirped rf pulse is orders of magnitude superior to case (1). In this case the switching can be accomplished using pulses of arbitrarily low power (in the absence of damping), albeit with a switching time inversely proportional to the value of the applied rf field. Switching times do not depend on the value of anisotropy and saturation magnetization. Not only does the switching occur much faster than for the case of nonchirped pulses, it is also more stable with respect to the random changes in the pulse parameters.

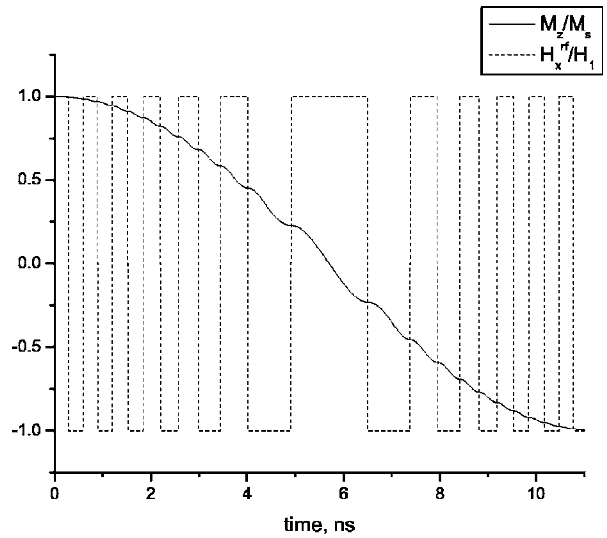

FIG. 3. Values of phase, M_z, M_x, and frequency as a function of time for $H_1=100$ Oe.

The program used for these simulations is available for the public use at www.rkmag.com. This work was supported by the National Science Foundation under Grant No. ESC-02-24210 and by DOE Grant DE-FG02–06ER46278.

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