Coherent control of precessional dynamics in thin film permalloy

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We demonstrate a method of eliminating overshoot and ringing in magnetization dynamics when the system bandwidth includes the intrinsic ferromagnetic resonance (FMR). The method employs staggered step excitation for the cancellation of FMR oscillations while maximizing the risetime of the magnetization response. The second-harmonic magneto-optic Kerr effect is used to measure the magnetic response at a localized spot on the sample. The measured response is adequately modeled with the Landau–Lifshitz–Gilbert differential equation. We explain the observed behavior in terms of destructive interference. [S0003-6951(00)02915-6]

The precessional oscillation of magnetization has been observed in numerous time-domain switching experiments.[1–4] This ''ringing'' in the magnetization response is the natural result of ferromagnetic resonance (FMR), an intrinsic property of all ferromagnetic materials.[5] As a result of the FMR oscillations, the total observed time of magnetization rotation from one equilibrium state into another in response to an applied magnetic field is actually much longer than the initial magnetization risetime: Damping of the oscillations typically requires multiple precessional cycles. Therefore, the ringing presents a serious impediment to realizing fundamentally limited data transfer rates in magnetic data storage.

In this letter we present a simple technique to suppress resonant oscillations by the proper temporal tailoring of the driving magnetic field pulse.[6] The idea is based on the principle of destructive interference when adding two coherent signals. While such a principle is not new and commonly applied in the context of control theory,[7] this is a demonstration of its use for the coherent control of ferromagnetic response. As shown below, this approach can significantly suppress the ringing without seriously compromising the magnetization risetime.

Coherent interference in a magnetic system was verified with the apparatus shown schematically in Fig. 1. The magnetic sample used in the experiment was a Permalloy ($Ni_{81}Fe_{19}$) film 50 nm thick, 500 μm wide, 5 cm long, grown by dc magnetron sputtering on a Si substrate 100 μm thick. The film was positioned on the top of the 500 μm wide center conductor of a coplanar waveguide of 50 Ω impedance and terminated with a short immediately following the sample. A commercial step generator produced voltage pulses of 10 ns duration and 50 ps risetime with a repetition rate of 1 MHz. These pulses were delivered to the shorted waveguide with a high-bandwidth coaxial cable of 50 Ω impedance. The pulse of 50 ps rise time is almost a perfect step excitation within the context of the present measurements. The reflection coefficient ρ for the short is $\rho=-1$. However, since the reflected pulse is traveling in the opposite direction, the two field steps (incident and reflection) are of the same polarity. The propagating step excitation and its reflection from the shorted termination produce a magnetic field pulse that, *at any given position*, is composed of two equal steps with a time separation which depends on the relative position of the observation point and the short. This is shown schematically in the inset of Fig. 1. The time separation of the two steps t_s is given by $t_s=2L/v_g$, where L is the relative distance to the short and v_g is the group velocity of the propagating electromagnetic wave in the loaded coplanar waveguide. The group velocity was found to be 1.2×10^8 m/s by time domain reflectometry.

The sample was oriented with the easy axis parallel to the waveguide (along the x axis in Fig. 1) such that the magnetic fields produced by the current in the waveguide were directed along the hard-axis direction (i.e., along the y axis in Fig. 1). A dc bias field of 760 A/m (9.6 Oe) was applied with external Helmholtz coils (not shown) along the easy-axis direction to eliminate any domain structure and enhance the precessional ringing by reducing the damping of the resonance.[3,4] These experimental conditions were optimal for testing our ability to control the ringing.

The magnetization's time response to the shaped step driving field was measured at different observation points along the waveguide by the time-resolved second-harmonic

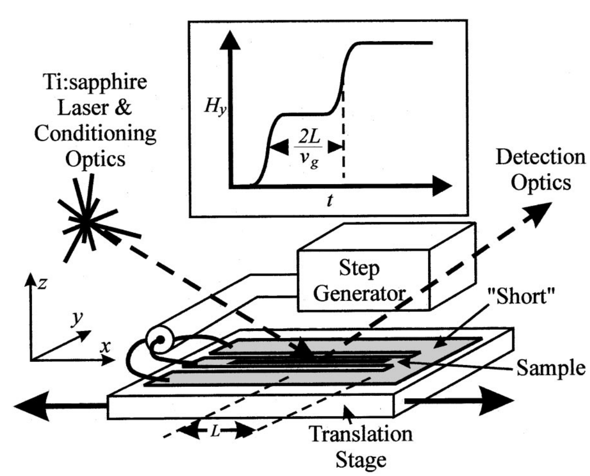

FIG. 1. Diagrammatic sketch of the experimental arrangement used to demonstrate coherent control of magnetization dynamics in a thin film sample.

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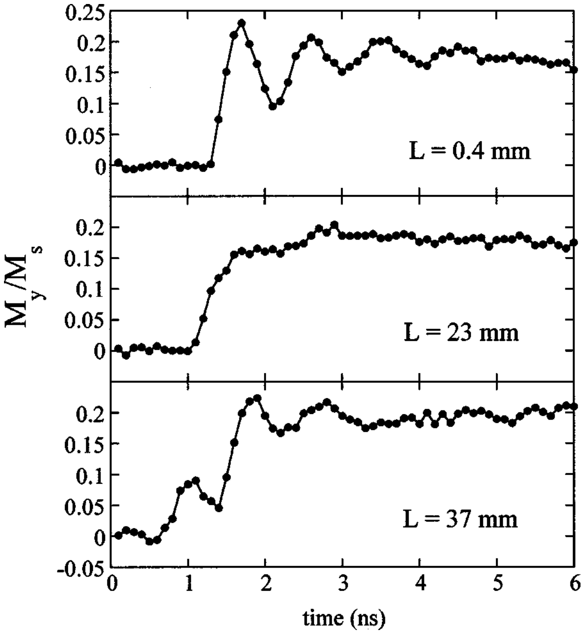

FIG. 2. Time-resolved SH-MOKE data for 50 nm thick Permalloy. The upper, middle, and lower graphs were obtained at spots of 0.4, 23, and 37 mm, respectively, from the shorted termination. The equivalent time delays between the arrival of the first and second field steps for the three sets of data are 7, 380, and 620 ps.

magneto-optic Kerr effect (SH-MOKE) technique.[4] Short (60 fs) optical pulses at a wavelength of 800 nm from a commercial mode-locked Ti:sapphire laser were incident on the sample at an angle of 45° in a *p*-polarized configuration. The spot size for the measurement was 5 μm. The second harmonic signal generated at the surface of the sample was directed through an interference filter and a triangular prism, both used to suppress the fundamental component of the incident light. Detection was accomplished with a photomultiplier tube operating in a coincidence detection mode. In this configuration, the measured contrast is proportional to the y component of the magnetization. The observation points were selected by moving the waveguide with respect to the incident light. In this fashion, we could continuously vary t_s for the drive pulse by measuring the sample response at any given spot. (We can consider spots measured millimeters apart as essentially uncoupled given the relatively short propagation distances of 100–200 μm for spin waves at $\sim$1 GHz in a metallic film.[8])

In Fig. 2 we show data measured at three locations along the waveguide: $L=0.4$, 23, and 37 mm. The equivalent time delays for the resulting pulses are $t_s=7$, 380, and 620 ps. The data in the upper graph in Fig. 2 are obtained at $L=0.4$ mm where the separation between the two steps is virtually nonexistent. Here, the response exhibits a typical time domain FMR, where the precessional decay time of several nanoseconds indicates relatively weak spin-lattice coupling. The time required for the magnetization to reach the first peak is approximately 350 ps. By breaking the step excitation into two steps with a precisely adjusted delay of 380 ps between them, we are able to completely suppress the FMR oscillations, as seen in the middle graph of Fig. 2. Finally, the response at $L=37$ mm again exhibits resonant oscillations, but shows that the y magnetization component undergoes two distinct changes in magnitude before settling about its final equilibrium, as expected given the large delay between the component steps in the pulse.

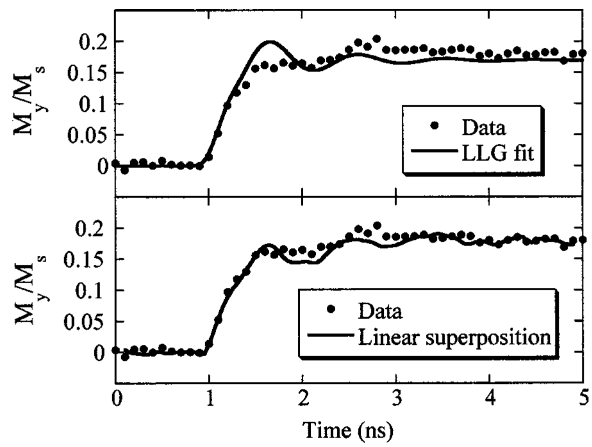

FIG. 3. Modeling of time-resolved SH-MOKE data obtained at $L=23$ mm. The upper model uses a numerical solution of the Landau–Lifshitz–Gilbert equation where the damping and field step amplitude are obtained by a fit to the data at $L=0.4$ mm. The source term is calculated assuming a linear superposition of two 100 ps risetime steps staggered with a 380 ps delay. The lower model uses a linear superposition of the data obtained at $L=0.4$ mm with a time shift of 380 ps.

The physics behind the suppression of precessional ringing is easily modeled using the Landau–Lifshitz–Gilbert (LLG) differential equation for magnetic motion of a single-domain particle: $d\mathbf{M}/dt=-|\gamma|\mu_0\mathbf{T}$-$(\alpha/M_s)(\mathbf{M}\times d\mathbf{M}/dt)$, where $\mathbf{M}$ is the magnetization vector, M_s is the magnitude of $\mathbf{M}$, and μ_0 is the permeability of free space. There are two fundamental constants of gyromagnetic motion in the LLG equation: the gyromagnetic ratio γ and the damping constant α. The generalized torque $\mathbf{T}$ is derived from the free energy density U of the system: $\mathbf{T}=-\nabla U$. We model U with the standard Stoner–Wohlfarth approximations for uniaxial anisotropy.[9] Both γ and the anisotropy field H_k are extracted by measuring the frequency of the precessional ringing at $L=0.4$ mm as a function of applied bias field along the easy-axis direction,[4] with the results $H_k=570$ A/m (7.1 Oe) and $\gamma=167$ GHz/T. Having determined H_k, we then ascertained a total drive pulse amplitude (incident+reflected) of 230 A/m (2.9 Oe), as required to swing the magnetization to 18% of saturation. A damping of $\alpha=0.015$ is obtained by a least-squares nonlinear fit of the data for $L=0.4$ mm to LLG. We then solve LLG for the case of the staggered-step excitation produced for $L=23$ mm, with the result shown in the upper graph of Fig. 3. The agreement with the experimental data is good, considering that all the physical parameters were fixed when solving LLG for the case of the staggered-step excitation.

An intuitive explanation for the elimination of precessional decay with a staggered-step excitation may be found in the lower graph of Fig. 3. In this case, the measured response at $L=0.4$ mm is simply superimposed upon itself, but with a time shift of $2L/v_g$, where $L=23$ mm. Again, we find a remarkable fit to the data obtained at $L=23$ mm. Thus, we see that simple linear interference effects lead to the elimination of precessional ringing: the arrival of the second field step at the exact moment when the magnetization reaches its maximum excursion due to the first field step results in the cancellation of any further precessional ringing.

(The use of a linear analysis is justified in this case since the range of magnetic motion is small enough to use the linearized version of LLG.[3]) If the second field step arrives too late after the magnetization reaches peak value, then the ringing is not suppressed and the magnetization is further driven by the second step, as can be seen at the bottom of Fig. 2 for the case of $L = 37$ mm.

The rise time of the magnetization for $L = 23$ mm is ~450 ps, only 100 ps longer than that observed for $L = 0.4$ mm. Numerical LLG modeling suggests that the rise time should not increase for zero damping, and complete cancellation of the oscillations should occur for pulses of identical amplitude. Nonzero damping causes the increase in the measured rise time; the oscillation amplitude of the initial step response is already slightly attenuated by the time the second field step arrives, abrogating perfect destructive interference. Given that real materials typically exhibit nonzero damping, a two-stage step excitation with identical step heights is not the ideal pulse shape for the complete removal of ringing. To optimize the coherent control of ringing in the case of non-negligible damping, the second step excitation must be attenuated in proportion to the degree of damping that occurs during the first half cycle of magnetic response. Therefore, it is theoretically possible that a properly shaped drive pulse can extract *all* the energy trapped in the form of gyromagnetic precession, regardless of the material parameters.

We note that this control of ringing is created by changing only the temporal delay between the two pulses, which if used separately would each cause FMR ringing. While other approaches can also eliminate FMR ringing (e.g., the use of thick magnetic films with eddy currents or the use of longer risetime current pulses), these approaches hinge on the ability to restrict the total bandwidth of the magnetic response such that it is *lower* than the fundamental bandwidth limit. (In the case of critical damping for a system exhibiting ideal second order linear response, the risetime increases by 50% when the damping is raised to the point of negligible overshoot.[7]) In contrast, the technique used here demonstrates the possibility for obtaining precession-limited risetimes irrespective of the material damping.

Such coherent control techniques would be targeted toward high speed magnetic storage applications, where data rates are rapidly approaching the microwave regime. The presence of precessional ringing following magnetization reversal could be a severe impediment to device performance if not properly controlled. The use of coherent-control methods will permit the operation of magnetic data-storage devices at fundamental frequency limits without concern for the adverse effects of FMR oscillations.

Note added in proof: Bauer *et al.*[10] have independently demonstrated the suppression of dynamical precession through the precise control of magnetic pulse duration. They used time-resolved *linear* magneto-optics, impulse excitations, and a bismuth iron garnet film, proving that coherent control is a general concept that can be applied to a wide variety of magnetic materials under differing experimental conditions.

[1] W. Dietrich and W. E. Proebster, J. Appl. Phys. **31**, 281S (1960).
[2] W. K. Hiebert, A. Stankiewicz, and M. R. Freeman, Phys. Rev. Lett. **79**, 1134 (1997).
[3] T. J. Silva, C. S. Lee, T. M. Crawford, and C. T. Rogers, J. Appl. Phys. **85**, 7849 (1999).
[4] T. M. Crawford, T. J. Silva, C. W. Teplin, and C. T. Rogers, Appl. Phys. Lett. **74**, 3386 (1999).
[5] Charles Kittel, *Introduction to Solid State Physics*, 6th ed. (Wiley, New York, 1986), p. 480.
[6] T. M. Crawford, T. J. Silva and C. T. Rogers, *Digest of the 43rd Annual Conference on Magnetism and Magnetic Materials* (AIP, College Park, MD, 1998), paper FE-09.
[7] R. C. Dorf, *Modern Control Systems*, 5th ed. (Addison-Wesley, New York, 1990), p. 97.
[8] P. Kabos and V. S. Stalmachov, *Magnetostatic Waves and their Applications* (Chapman & Hall, New York, 1994), p. 57.
[9] E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London, Ser. A **240**, 599 (1948).
[10] M. Bauer, R. Lopusnik, J. Fassbender, and B. Hillebrands (unpublished).