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Magneto-optical imaging of vortex domain deformation in pinning sites

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ABSTRACT

We use a sensitive magneto-optical microscopy technique to image the magnetization response of micron-scale ferromagnetic disks to changes in applied magnetic field. This differential technique relies on a modulated applied magnetic field which allows us to measure changes in magnetization <1% with sub-micron resolution. The disks are magnetized in single vortex domains, with defects in the material serving to pin the vortex core at particular positions. By applying a small AC magnetic field, we measure the deformation of the magnetization while the core remains pinned. We can also characterize the strength of the pinning site by increasing the AC magnetic field to unpin the vortex core. While pinned, we find that the magnetization away from the core reorients slightly to better align with an applied field. Additionally, an applied field causes the pinned core itself to tilt in the direction of the field. Once the field is large enough to unpin the core, this tilt disappears, and the core instead translates across the disk.

1. Introduction

The controlled movement of domain walls in micromagnetic structures is of increasing interest with promising applications as spintronic storage devices [1,2] and logic elements[3]. As a result it is important to gain an understanding of domain wall dynamics. The presence of impurities and intrinsic material defects, found in all real samples, affects the mobility of domain walls causing them to be trapped at pinning sites [4–8]. Thin disks composed of soft magnetic materials have been shown to exhibit a ground-state vortex structure, which is characterized by a single large curl of in-plane magnetization and a central vortex core region of magnetization normal to the plane [9–11]. The high energy density of the central vortex region enhances local interaction with pinning sites [12,13], making these structures well suited for studying domain dynamics in the presence of disorder.

Previous work has studied the dynamics of magnetic vortices and their interaction with pinning sites by means of micro-Hall magnetometry [4,14,15], Lorentz transmission electron microscopy [5,16,17], and scanning x-ray transmission microscopy [18]. Optical probing by means of time-resolved Kerr microscopy has allowed for the measurement of gyrotropic frequency suppression in the presence of naturally occurring pinning sites [6,19,20]. Recent work has begun considering the magnetic-field-induced deformation of the vortex domain structure while it is pinned [21], and indirect experimental evidence for the pinned vortex deformation has been seen [22].

Here, we develop and use a sensitive magneto-optical technique to image the magnetization response to a change in magnetic field of both pinned and unpinned vortex domains, with sub-micron resolution. By modulating both the probe laser and the applied magnetic field, we achieve sufficient sensitivity to map out the deformation of the vortex domain structure while it is trapped in a pinning site. A similar technique was used in Ref. [20] to measure temporal dynamics of magnetic domains – here we focus on static magnetization maps. We find that the in-plane magnetization away from the pinned vortex core deforms to better align with the applied field, as predicted by [21,22]. Additionally, we find that an asymmetry in the out-of-plane component of the magnetization arises when the vortex is deformed, which we attribute to a tilting of the pinned vortex core. In both the pinned and unpinned cases, we also measure an out-of-plane magnetization component near the edge of the structures, likely due to the magnetostatic charge that is induced on the adjacent sides of the magnetic disks. These results provide a more detailed picture of the process of domain pinning and unpinning, and may lead to more accurate modeling of domain wall motion.

2. Methods

A schematic of the sample is shown in Fig. 1(a). A 100-nm-thick gold stripline waveguide was patterned via photo-lithography and

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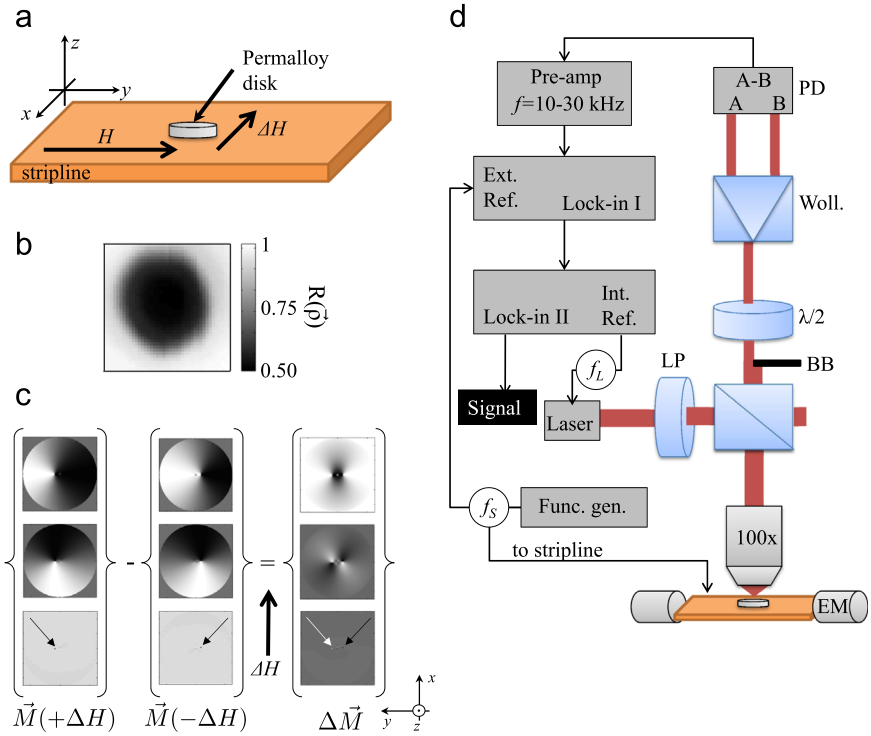

Fig. 1. (a) An illustration of a Permalloy disk atop the gold microstripline. A constant field is produced by an electromagnet along the y-direction and an alternating field is produced along the x-direction by an alternating current through the stripline. (b) A map of $R(\vec{\rho})$, the intensity of reflected light, taken by raster scanning using the polar MOKE configuration. These maps are used to normalize the $\Delta\tilde{M}_\alpha$ maps shown in Fig. 3. (c) Simulated maps of the M_α component of magnetization with an applied field of $\pm\Delta H = 600$ A/m, where $\alpha = x, y, z$ from top to bottom respectively. The difference of these maps is taken to generate the contrast map ΔM_α. Arrows indicate the small feature from the vortex core. (d) An illustration of the important optical and electronic components of the experiment. Here LP is a linear polarizer, BB is a beam blocker, $\lambda/2$ is a half-wave plate, Woll. is a Wollaston prism, PD is a balanced photo-detector, and EM is an electromagnet.

thermal evaporation on a sapphire substrate. The stripline tapers to a 10 µm width at the center. Atop this central region of the stripline, 30 nm thick Permalloy ($Ni_{0.81}Fe_{0.19}$) disks (diameter $d = 1$ and 2 µm) were fabricated via electron beam lithography, electron beam evaporation, and liftoff. Naturally occurring defects in the Permalloy serve as pinning sites for the vortex core.

The experimental setup (Fig. 1d) is based on a standard scanning magneto-optical Kerr effect (MOKE) microscope [23]. A diode laser ($\lambda = 660$ nm) is sinusoidally modulated at frequency $f_L = 200$ Hz, and is linearly polarized and focused onto the sample through a 100 × oil immersion objective (numerical aperture, NA = 1.25). The sample is mounted on a three-axis piezo-driven stage, and is situated between the poles of an electromagnet which supplies a constant magnetic field H_0 in the y-direction. The reflected light is collected back from the objective, and the Kerr rotation is measured using a balanced photo-diode detector. The measurement can be carried out by either collecting all the reflected light, or by blocking the bottom, or left half of the reflected beam. When all the probe light is collected, the Kerr rotation measures the out-of-plane magnetization component M_z. When half the beam is blocked, the collected light has reflected off the sample at a nonzero average angle of incidence, and therefore is also sensitive to the in-plane M_x or M_y magnetization component when blocking the bottom or left half, respectively.

An in-plane alternating magnetic field with amplitude ΔH was applied to the sample in the x-direction by running a square wave current through the waveguide at frequency $f_S = 15$ kHz. The damping time for these magnetic domains are on the order of $t_d \sim 100$ ns [24]. Because $f_S \ll t_d^{-1}$, we can assume that the magnetization alternates between two static configurations at $\pm\Delta H$. There is a component of the MOKE signal arising from the difference in magnetization between $\pm\Delta H$ which will be modulated at frequency $f_S \pm f_L$. The signal from the balanced photodiode detector was passed through an amplifier equipped with a band-pass filter from 10 kHz to 30 kHz. This filter removes any part of the signal not arising from the Kerr effect, such as reflection off of the waveguide when the laser spot is near the edge of the sample. The signal is then sent to a lock-in amplifier with reference frequency f_S, and time constant 640 µs. The output of the first lock-in amplifier is sent to a second lock-in amplifier with reference frequency f_L with time constant 200 ms.

In a traditional scanning MOKE microscopy measurement only the probe laser is modulated, and after a single lock-in, magnetization over the surface of the sample $\vec{M}(\vec{\rho}, \vec{H})$ is measured, where $\vec{\rho}$ is the two-dimensional position vector [23]. The different components of $\vec{M}$ are determined separately by blocking or unblocking the probe beam, as described above. This technique is particularly problematic near the edges of magnetic structures, or for small samples where the probe is always near an edge. The presence of reflection from the underlying substrate and polarization effects due to the edges, in conjunction with sample vibration or position drift, translate into large sources of noise and signal drift. These problems are largely eliminated with the addition of the alternating field ΔH, and the second lock-in amplifier. In this case, we probe the change in the magnetization $\Delta\vec{M}(\vec{\rho}, H, \Delta H) = \vec{M}(\vec{\rho}, \vec{H} + \Delta\vec{H}) - \vec{M}(\vec{\rho}, \vec{H} - \Delta\vec{H})$. The measured signal $\Delta\tilde{M}$ with the probe spot centered at position $\vec{\rho}$ is the convolution of the focused probe profile $I(\vec{\rho})$ and $\Delta\vec{M}$

$$\Delta\tilde{M}_\alpha\left(\vec{\rho}, H, \Delta H\right) = \int I_\alpha\left(\vec{\rho} - \vec{\rho}'\right)\Delta M_\alpha\left(\vec{\rho}', H, \Delta H\right) d^2\rho', \qquad (1)$$

where $\alpha = x, y, z$. In general, the focused probe profile depends on α, because of the different beam blocking geometries. I_z is radially symmetric, whereas I_x and I_y are elongated in the x- and y-directions respectively, resulting in some distortion of the images.