

Ultrafast Magnetisation Dynamics of Spintronic Nanostructures

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Abstract

The ultrafast (sub-nanosecond) magnetisation dynamics of ferromagnetic thin films and elements that find application in spintronic devices is reviewed. The major advances in the understanding of the magnetisation dynamics in the two decades since the discovery of giant magnetoresistance and the prediction of spin transfer torque are discussed, along with the plethora of new experimental techniques developed to make measurements on shorter length and time scales. Particular consideration is given to time resolved measurements of the magneto optical Kerr effect and it is shown how a succession of studies performed with this technique have led to an improved understanding of the dynamics of nanoscale magnets. The dynamics can be surprisingly rich and complicated, with the latest studies of individual nanoscale elements showing that the dependence of the resonant mode spectrum upon the physical structure is still not well understood. Finally the article surveys the prospects for development of high frequency spintronics devices and highlights areas in which further study of fundamental properties will be required within the coming decade.

Key words or phrases

Ultrafast spin dynamics

Time-resolved magneto-optical Kerr effect

Pump-probe

Nanomagnet

Magnetisation precession

Confined spin wave

Introduction

Spintronics is concerned with the delivery of new functionality within electronic devices through the exploitation and manipulation of the electron spin. While magnetoresistance effects associated with electron spin have been known for a long time (Thomson 1856), most authors agree that the field of spintronics began with the observation of giant magnetoresistance (GMR) (Baibich *et al.* 1988, Binasch *et al.* 1989) and tunnel magnetoresistance (TMR) (Julliere 1975) in artificially structured multilayer materials, which have dominated sensor applications within data storage technology since the turn of the Millennium. These structures contain ferromagnetic layers that act as sources of spin-polarised electrons and provide spin-dependent electron scattering, that may have a bistable ground state, and that, crucially, provide robust operation at room temperature. This article is concerned principally with spintronic materials that contain metallic ferromagnets and does not attempt to discuss the equally interesting field of semiconductor spintronics in which spin polarisation may instead be generated by the Spin Hall Effect and manipulated by effective magnetic fields resulting from the spin-orbit interaction.

The most immediate applications of spintronics lie within information technology in the broadest sense, and so the primary concerns in evaluating the performance of spintronic technology are its potential for miniaturisation, its speed of operation, and the allied issues of power consumption, endurance, sustainability and cost. Since node sizes within rival semiconductor technology have recently been reduced to 22 nm, research is increasingly directed towards devices with sizes in the deep nanoscale regime that must operate at GHz frequencies for use in data storage, logic and communications applications. This article is concerned specifically with the dynamic behaviour of the ferromagnetic materials and elements that form the building blocks of such devices. Their dynamical response must be first understood and then controlled. While experimental studies of such processes are often extremely challenging, it will be shown that the relationship between physical structure and magnetic response is both intimate and intricate leading to rich and varied dynamic phenomena.

The first section of this article charts the development of our understanding of magnetisation dynamics within confined magnetic structures and of the associated experimental techniques during the past two decades. Particular emphasis is placed upon magneto-optical measurements that are both non-invasive and possess a high degree of spatial resolution. The power of these techniques is demonstrated in the following section with the presentation of a series of measurements that reveal the major features of precessional dynamics within nanoscale magnetic structures. However, the interpretation of measurements made upon arrays of nominally identical elements may be complicated both by inhomogeneous broadening, and interactions between elements that lead to

collective modes of excitation. The section culminates with studies of individual nanomagnets, which are designed to circumvent these problems. Finally, future directions in the investigation and exploitation of dynamical processes are discussed.

Dynamical phenomena and measurement techniques

Research into thin film magnetism, including magnetisation dynamics, has in the past been driven by the needs of the data storage industry. For example, flux propagation in the yoke and switching of the pole pieces of a miniaturised electromagnet underlies the operation of the write transducer, while quasi-coherent rotation of the magnetisation in a thin film element is exploited in magnetoresistive readout. The discovery of GMR and TMR led to the use of more sensitive yet more complicated multilayer stacks within the readout device and also made feasible the development of magnetic random access memory (MRAM) with pulsed field writing and magnetoresistive readout. Over the past twenty years the need for higher data storage densities and reduced access times has seen the development of a rich variety of new experimental techniques to study magnetic processes at high frequencies and on short timescales in microscale and nanoscale ferromagnetic structures. These techniques may be broadly categorised as employing either electrical, optical or x-ray probe mechanisms.

The magnetoresistance of a sensor or MRAM device may itself be used to study dynamic processes. Time-resolved tunnelling magnetoresistance (TR-TMR) (Koch *et al.* 1998) was used to demonstrate precessional switching of the magnetisation in a rectangular microscale element that formed the free layer of a magnetic tunnel junction. In this technique the magnetisation dynamics were detected simply by measuring the change in the TMR as the magnetisation rotated with respect to a fixed polarising layer. Other electrical measurement techniques include pulsed inductive microwave magnetometry (PIMM) (Silva *et al.* 1999) and vector network analyser ferromagnetic resonance (VNA-FMR) (Neudecker *et al.* 2006), in which ferromagnetic elements are integrated with a microscale, impedance matched planar waveguide that is used to deliver either a pulsed (PIMM) or harmonic magnetic field (VNA-FMR) to the sample. PIMM is performed in the time-domain. The dynamics are detected by using a sampling oscilloscope to measure the time varying voltage induced on the waveguide by the dynamic stray fields generated by the precession of the sample magnetisation. PIMM is well suited to the study of sensor dynamics and has been used to study the variation of the spectroscopic splitting or g -factor (Nibarger *et al.* 2003) and damping from the linear to the non-linear regime (Gerrits *et al.* 2006). In contrast VNA-FMR is performed in the frequency domain. The magnetisation dynamics are detected by comparing the amplitude and phase of an outgoing microwave signal, generated by the VNA, and an incoming

microwave signal that is either reflected or transmitted by the sample. VNA-FMR has a wide dynamic range and is able to detect additional resonance modes that either have small amplitude or which couple weakly to a particular probe or stimulus in other measurement techniques. It has enabled the full magnetostatic mode spectrum of microscale elements to be explored and the band structure of arrays of interacting magnetic elements, so called magnonic crystals, to be observed (Neusser *et al.* 2009). While PIMM and VNA-FMR can be used to study microscale and nanoscale elements, typically the sample must fill a significant proportion of the measurement antenna in order to generate a detectable signal.

With the advent of x-ray magnetic circular dichroism (XMCD), and x-ray magnetic linear dichroism (XMLD), x-ray techniques have been used extensively to characterise the magnetic properties of magnetic thin film multilayers with element specificity. TR-XMCD was used to separate the time dependent response of the pinned and free layers of spin-valve samples (Bonfim *et al.* 2001), since their relative orientation is of most interest in understanding magnetoresistive response. More recently x-ray photo emission electron microscopy (XPEEM), and magnetic transmission x-ray microscopy (MTXM) have utilised XMCD as a magnetic contrast mechanism in order to image the domain structure of microscale and nanoscale elements with a spatial resolution of a few tens of nanometres. Since 2004, XPEEM (Raabe *et al.* 2005) and MTXM (Stoll *et al.* 2004) have been used to obtain TR images of sub-nanosecond magnetisation dynamics in response to a time dependent magnetic field that have unrivalled spatial resolution. However, these measurement techniques are limited by the temporal resolution imposed by the x-ray pulse width (typically tens of ps, although shorter pulses are possible using pulse slicing techniques or from free electron lasers (Durr *et al.* 2009)) and the magnetic resolution. For this reason the first studies concentrated upon the gyration of vortices that offer large magnetic contrast at MHz frequencies (Stoll *et al.* 2004, Raabe *et al.* 2005). Since then, switching of the vortex core polarisation between bi-stable states using a time-varying magnetic field has been demonstrated (Van Waeyenberge *et al.* 2006). Alternatively, x-ray ferromagnetic resonance (XFMR) has been developed for the study of element specific GHz magnetisation dynamics in response to either pulsed (Bailey *et al.* 2004) or harmonic (Boero *et al.* 2005) magnetic fields, albeit with a spatial resolution of a few tens of micrometres. Phase resolved XFMR is particularly powerful and has shown, for example, that rare earth (RE) atoms are the source of damping in alloys with transition metals (TM) since the precession of the RE lags that of the TM (Arena *et al.* 2007).

Optical techniques have been used extensively for the study of magnetisation dynamics in microscale and nanoscale elements. In the frequency domain, Brillouin light scattering (BLS) detects light inelastically scattered from spin waves (Demokritov *et al.* 2001). BLS has a wide dynamic range and sufficiently high sensitivity for the detection of low amplitude thermally excited

spin waves. A wide variety of spin wave excitations including Damon-Eshbach (DE) modes and perpendicular standing spin wave (PSSW) modes can be detected. Recently, BLS has been used to detect the spin wave eigenmodes of nanoscale ferromagnetic elements, in addition to the splitting of the normal modes of interacting elements within arrays (Gubbiotti *et al.* 2006, Gubbiotti *et al.* 2007). Spatial resolution has been improved in micro-focus BLS experiments yielding images of spin wave radiation from a spin valve (Demidov *et al.* 2005). The addition of TR capability to BLS has yielded TR images of the propagation of confined spin-waves within microscale structures (Demidov *et al.* 2009).

In the time domain, the magneto-optical Kerr effect (MOKE) has proved to be a powerful tool for the study of magnetisation dynamics. MOKE allows a change in the magnetisation to be detected as a change in the polarisation and/or intensity of light reflected from a ferromagnetic material. Typically in TR-MOKE experiments, an ultrafast laser is used to perform a stroboscopic pump-probe experiment for which each laser pulse is split into pump and probe pulses that are used to excite and detect the magnetisation dynamics respectively. By varying the time delay of the probe pulse with respect to the pump, the temporal evolution of the magnetic response of the sample can be mapped by recording the MOKE signal at each time delay. The magnetisation dynamics may be excited either directly using an intense laser pulse (Beaurepaire *et al.* 1996), or by a time-varying magnetic field that is either triggered by or synchronised to the laser (Freeman *et al.* 1991). The use of a sub-100 fs laser pulse as a pump leads to rapid heating of the ferromagnetic sample near to, or above the Curie temperature resulting in an ultrafast demagnetisation on femtosecond timescales (Beaurepaire *et al.* 1996). During the recovery of the magnetisation, changes in the anisotropy field can exert torque on the magnetisation leading to magnetisation dynamics on picoseconds timescales (van Kampen *et al.* 2002, Liu *et al.* 2010). Optical pulses can also excite precessional motion of magnetisation non-thermally e.g. via the inverse Faraday effect (Kimel *et al.* 2004). The spatial resolution of TR-MOKE experiments can be significantly enhanced by using a scanning microscope. In time-resolved scanning Kerr microscopy (TRSKM) (Hiebert *et al.* 1997), magnetic samples are integrated with a microscale planar waveguide so that a pulsed (Freeman *et al.* 1996) or harmonic magnetic field (Tamaru *et al.* 2004) may be used to excite magnetisation dynamics. The high spatio-temporal resolution of TRSKM makes it a powerful tool with which to study the magnetisation dynamics of individual submicron ferromagnetic elements. One of the first applications was to image the switching of the pole pieces of a recording head (Freeman *et al.* 1996). A vector-resolved version of TRSKM, capable of measuring three orthogonal components of the magnetisation vector, allowed the trajectory of the magnetisation precession to be determined (Acremann *et al.* 2000, Hiebert *et al.* 2002), and led to the demonstration of precessional switching of a micrometer sized magnetic element (Gerrits *et al.*

2002, Hiebert *et al.* 2003). Non-linear probe mechanisms have also been employed, in the form of magnetic second harmonic generation (Crawford *et al.* 1999, Gerrits *et al.* 2002, Gerrits *et al.* 2004) that may in principle yield surface sensitivity, or cubic non-linearities that probe linear and orbital momentum relaxation times (Kruglyak *et al.* 2005b)

A further technique that lies beyond the categories described above is magnetic resonance force microscopy (MRFM). The technique is based upon magnetic force microscopy (MFM) and utilises a sub-micrometer ferromagnetic sphere attached to the apex of a cantilever to detect the resonance modes of a nearby ferromagnetic element by means of their dipolar interaction. The element is magnetised out-of-plane, while magnetisation dynamics are excited using an in-plane harmonic field of fixed frequency that is modulated at the resonance frequency of the cantilever. Resonant modes are detected by measuring the amplitude of the cantilever as the applied magnetic field is swept. Excitation of the resonant modes leads to a reduction in the out-of-plane component of the magnetisation and a change in the amplitude of the cantilever. MRFM offers very high sensitivity and spatial resolution, and has been used to detect resonant modes (de Loubens *et al.* 2007) and non-linear spin wave excitations (de Loubens *et al.* 2005). Recently MRFM has been used to detect splitting of the gyration frequency of a vortex core within a nanoscale disc. The splitting was found to be due to bistable gyration modes corresponding to opposite core polarities at the same bias field (de Loubens *et al.* 2009), and has led to the proposal of a frequency-controlled magnetic vortex memory (Pigeau *et al.* 2010).

While the discovery of GMR has enabled the development of passive spintronic devices such as sensors, the potential for active devices was presaged by the prediction of spin transfer torque (STT) (Slonczewski 1989) and STT induced magnetic switching (Berger 1996, Slonczewski 1996). STT is associated with the partial transfer of spin angular momentum from an injected spin-polarised current to the macroscopic magnetisation of a ferromagnet. The STT excites precession within the ferromagnet that can result in stable precessional trajectories or switching, and so high frequency measurement techniques are required to understand both the origins and the consequences of the STT. Since the required current densities are large, and the action of the STT is frustrated by the conventional Oersted fields that result from Ampere's law, the effects of STT are most clearly seen in nanoscale electrical contacts. Unsurprisingly STT was first detected by electrical measurements since both the size of the device and the presence of a thick top contact frustrate the use of optical or x-ray measurement techniques. Tsoi *et al.* reported the first observation of STT excited spin waves in 1998 (Tsoi *et al.* 1998), while STT induced switching was first demonstrated experimentally by Katine *et al.* in 2000 (Katine *et al.* 2000), both using DC magnetoresistance measurements. The relevance of the STT switching of magnetic elements to data storage application was immediately recognised. While great efforts are being made to

suppress STT in recording head sensors, STT writing is expected to underpin the development of a second generation of MRAM cell. It was also realised that the large amplitude spin waves excited in STT devices could be used to create on-chip microwave sources – so called spin torque oscillators (STOs) (Kiselev *et al.* 2003). The output power of an isolated STO is insufficient for most applications e.g. in wireless communication. A solution to this problem was proposed in 2005 with the reported phase-locking of two STOs integrated on a single chip, although the phase locking of greater numbers of STOs and the necessary mechanisms of interaction are still the subject of intense research (Kaka *et al.* 2005, Mancoff *et al.* 2005). STT may also be exploited within an individual ferromagnet in order to drive the motion of a domain wall (Yamaguchi *et al.* 2004), and this has led to proposals for new types of memory device, for example “racetrack memory”, in which data is stored sequentially as domains of opposite magnetisation within a nanowire (Parkin *et al.* 2008).

Since the initial DC electrical detection of STT, researchers have devised other increasingly ingenious methods to detect STT driven precessional dynamics. When the device is driven by a constant current source, the changing magnetoresistance of the device gives rise to voltage oscillations that may be detected with a spectrum analyser. Indeed thermally excited noise oscillations may be detected in a similar manner. However if the device is instead driven by a swept frequency microwave current, then mixing of the oscillatory source and magnetoresistance functions leads to a dc voltage, the spin-diode effect (Tulapurkar *et al.* 2005), that allows STT induced ferromagnetic resonance (STT-FMR) modes of the device to be detected. STT-FMR has already been used to confirm the detailed functional form of the STT (Sankey *et al.* 2008). TR imaging techniques have recently been devised that are able to detect STT induced dynamics. TR-MTXM experiments have shown that switching in nano-pillars is a non-uniform process (Acremann *et al.* 2006), and that vortex gyration within a Landau closure domain structure may be induced by STT (Bolte *et al.* 2008). Finally, the observation of non-local STT induced switching, mediated by pure spin currents, in lateral transport structures (Kimura *et al.* 2006) suggests that imaging techniques will soon play a much greater role in study of STT.

Time-resolved scanning Kerr microscopy

The pump-probe apparatus used to study the time-evolution of picosecond spin dynamics of thin-film ferromagnetic materials in response to a pulsed magnetic field is shown schematically in Figure 1. After demonstrating the sensitivity of TR-MOKE to the trajectory of precession (Hicken *et al.* 1999), the TRSKM was used by Barman *et al.* (Barman *et al.* 2003) to image spin wave excitations in microscale square elements. More recently, the TRSKM has been integrated with a

microwave probe station that allows excitation of the magnetisation dynamics with a pulsed or harmonic magnetic field generated by an electronic pulse generator or microwave synthesiser that is phase-locked to the optical pulses from a Ti:sapphire laser (Neudert *et al.* 2008). The emerging laser pulses, with sub-100 fs duration, 800 nm wavelength, and 80 MHz repetition rate, are used to generate pulses of 400 nm wavelength (blue) by second harmonic generation in order to enhance the spatial resolution of the microscope. The blue beam is expanded ($\times 5$) to reduce the beam divergence before being linearly polarised and focused to a near diffraction limited spot of ~ 300 nm diameter using a $\times 60$ microscope objective lens. The change in the out-of-plane component of the precessing magnetisation is detected by measuring the small ($\sim 10^{-3}$ μdeg) rotation of the plane of polarisation of the optical probe reflected from the sample surface due to the polar MOKE. Characterisation and improvement of the mechanical stability, combined with the enhanced spatial resolution, have allowed the magnetisation dynamics of single nanomagnets with lateral dimensions as small as 220 nm to be measured on picosecond timescales.

Magnetisation dynamics in arrays of nanomagnets

Much of the understanding of the magnetisation dynamics of nanomagnets has been determined from experiments performed upon arrays of nanomagnets. Previously experiments performed upon microscale elements and stripes provided valuable insight into the mechanisms that give rise to localisation of spin wave modes within confined magnetic structures. Jorzick *et al.* used BLS to study the spin wave spectra of long stripes of 1 μm width and 35 nm thickness (Jorzick *et al.* 2002). When the stripe was magnetised along its short axis, a low frequency dispersionless spin wave mode was detected in the BLS spectra. The mode was found to be a localised mode confined by the non-uniform internal magnetic field near to the long edges of the wire, perpendicular to the bias field. Bayer *et al.* used BLS to study the spin wave spectra of an array of $1 \times 1.75 \mu\text{m}^2$ rectangular elements of 35 nm thickness (Bayer *et al.* 2006). Calculations of dipole-exchange spin wave modes within a transversely magnetised stripe at 2 kOe revealed that higher frequency dipole-dominated spin wave modes have larger amplitude at the centre of the wire, while lower frequency exchange-dominated modes have large amplitude near to the edges of the wire. At 1 kOe the localisation of the modes was less clear as regions of zero internal field near to the long edges of the element began to migrate towards the center of the wire.

From the studies on microscale elements and stripes it was clear that the non-uniform internal field in confined magnetic structures gives rise to strong localisation of the dipole-exchange spin wave modes. For sub-micron and nanoscale elements, the in-plane demagnetizing field and the

non-uniformity of the internal field increase as the element aspect ratio (lateral size-to-thickness) is reduced (Keatley *et al.* 2008). The resulting richer mode spectra lead to a less uniform magnetic response to a uniform field pulse. In addition, since both the internal field and the static magnetisation are non-uniform, micromagnetic simulations are necessary in order to interpret the observed magnetisation dynamics within nanoscale elements.

Kruglyak *et al.* used TRSKM to study the spin wave spectra of square elements of 2.5 nm thickness and length ranging from 630 nm down to 64 nm (Kruglyak *et al.* 2005a). Fast Fourier transform (FFT) spectra calculated from the measured TR signals are shown in Figure 2(a). The frequency of the excited modes was observed to increase as the element size was reduced. However, a shift in the frequency from about 7 GHz to 5 GHz was seen as the element size was reduced below 220 nm. The results of micromagnetic simulations revealed that the shift in frequency was due to a change in the mode character from a mode with large amplitude at the center of the element, to a mode with large amplitude along the edges of the element perpendicular to the bias field, Figure 2(b). Furthermore, for the simulated element size of 220 nm the “center-“ and “edge-type” modes were found to coexist with similar amplitude.

Keatley *et al.* performed TRSKM experiments on elements of similar size and composition, but with an increased thickness of 13.6 nm (Keatley *et al.* 2008). The richer mode spectrum of thicker elements allowed the interplay between the center- and edge-type modes to be investigated more clearly. Again a size dependent crossover in the mode character was observed in the thicker elements. In addition a strong field dependence of the mode character was observed. For an element size of 236 nm a crossover from a higher frequency center mode to a lower frequency edge mode was observed at a bias field between 770 and 590 Oe. In larger and smaller elements the response was largely characterised by center- and edge-type modes respectively for much of the studied bias field range. Micromagnetic simulations of 3×3 arrays revealed that the crossover between center- and edge-type modes was mediated by the complicated evolution of the total effective field within the element. In addition below the crossover field the edge-type modes were not strictly localised at the edges as for the microscale stripes and rectangles studied by Jorzick *et al.* and Bayer *et al.* Instead, the edge-type modes were found to be slightly detached from the edge allowing the mode to extend throughout much of the volume of the nanomagnet. The crossover in the mode spatial character as the size of the element and/or the bias field was reduced, in addition to the delocalised spatial character of detached edge-type modes, were identified to be general characteristics of the magnetisation dynamics of square nanomagnets.

In 2007 Kruglyak *et al.* identified a dynamic configurational anisotropy of the magnetisation dynamics within $\sim 4 \times 4 \mu\text{m}^2$ arrays of square $220 \times 220 \text{ nm}^2$ nanomagnets of 2.5 nm thickness (Kruglyak *et al.* 2007a). The angular dependence of the magnetisation dynamics in arrays of square

nanomagnets was studied using TRSKM. In agreement with micromagnetic simulations, both the number of precessional modes and the values of their frequencies were observed to vary strongly as the orientation of the external magnetic field was rotated in the element plane. It was shown that the observed behavior could not be explained by the angular variation of the static effective magnetic field. Instead, it was found to originate from a dynamic configurational anisotropy resulting from a variation in the direction of the effective wavevector of excited spin wave modes with respect to the direction of the static magnetisation.

While the magnetisation dynamics of arrays of nanomagnets have been measured using TRSKM in order to determine the dynamic characteristics of individual nanomagnets, the emerging field of *magnonics* (Kruglyak *et al.* 2010a) utilises interelement interactions to modify and tailor dynamic magnetic properties in arrays of magnetic elements, or *magnonic crystals*, with the aim of supporting specific collective excitations. Kruglyak *et al.* used the high spatial resolution and phase sensitivity of TRSKM to directly image the spatial character of collective excitations in two-dimensional magnonic crystals for the first time (Kruglyak *et al.* 2010b). Figure 3 shows TRSKM images of three collective excitations with frequencies of 3.0, 3.6, and 4.2 GHz that were observed in a $\sim 4 \times 4 \mu\text{m}^2$ array of $80 \times 40 \text{ nm}^2$, 5 nm thick, stadium shaped elements with 20 nm edge-to-edge separation at a bias field of 200 Oe. For each mode, two images are shown that correspond to excitation of the mode using either an in-plane pulsed or harmonic magnetic field.

The spatial character of the collective excitations was found to be complicated by several contributions. Firstly, the linewidth of the modes was larger than the frequency splitting between the modes. Therefore, two or more of the collective excitations contribute to the observed spatial character, but with different amplitude. Secondly, the magnetic ground state of the array is expected to be non-uniform. In the absence of exchange coupling between neighbouring elements, the relatively weak bias field acts to align the magnetisation of neighbouring elements while the long range dipolar interaction between elements favours non-uniform alignment. As a result the collective excitations within the array exhibit regions of large amplitude that are canted relative to the edges of the array. The collective modes are confined within the array in a similar way to the confined modes of a single element. However, the magnetic properties of the array are related to the structure and geometry of the array and the constituent elements. Therefore, such arrays appear as magnonic metamaterials to collective excitations that have a wavelength much greater than the period of the array.

Magnetisation dynamics in individual nanomagnets

So far the dynamic behaviour of nanomagnets has been investigated largely by studying arrays of nanomagnets in order to obtain a sufficient signal. However, the inter-element dipolar interaction within arrays can introduce additional collective excitations (Keatley *et al.* 2008, Kruglyak *et al.* 2010b) that, while interesting, must be avoided by increasing the inter-element separation if the dynamic behaviour of an individual nanomagnet is to be clearly resolved. In addition, subtle differences in the structure of the different nanomagnets within an array, e.g. edge roughness, can lead to inhomogeneous broadening of the detected modes (Keatley *et al.* 2008) so that modes of slightly different frequency cannot be resolved. The appearance of collective modes and inhomogeneous broadening can be avoided if measurements can be made upon a single nanomagnet.

Figure 4(a) shows TR signals acquired from a $440 \times 440 \text{ nm}^2$ square and a $440 \times 220 \text{ nm}^2$ ellipse. The elements were single, isolated elements of 7 nm thickness. For the square, TR scans were performed for two orientations of the in-plane bias field. When a bias field of 200 Oe was applied along the edge, evidence of beating of the precessional signal was observed. As reported by Kruglyak *et al.* in 2005 and 2007, beating of the TR signals acquired from micro-arrays of square nanomagnets was found to indicate excitation of at least two types of spin wave mode, the so called centre- and edge-type modes. In Figure 4(b) the FFT power spectrum of the TR signal in Figure 4(a) is shown (shaded line and symbol). The spectrum reveals a main peak at 4.4 GHz that is in excellent agreement with spectra extracted from micromagnetic simulations (bold line). However, not all features of the experimental and simulated spectra agree. For example, the shoulder observed in the experimental spectra at ~ 2.5 GHz is not reproduced in the simulated spectra.

When the bias field was applied along the diagonal, the TR signal was found to have smaller amplitude and exhibit enhanced damping (Figure 4(a)). The FFT spectrum (Figure 4(b)) reveals a broader linewidth and lower frequency. The different magnetic ground state of the square when the field is applied along the diagonal may account for the shift to lower frequency, while the broadening may be due to the excitation of two or more modes that are observed in the simulated spectra, but that cannot be resolved experimentally.

For the ellipse (Figure 4), a bias field of 200 Oe was applied along the major axis. The TR signal in Figure 4(a) shows that the precession amplitude is smaller, while the damping is similar to that of the square for the same bias field orientation. The experimental spectra in Figure 4(b) show that the precession frequency of the ellipse is similar to that of the square. However, there are significant differences between the experimental and simulated spectra for the ellipse despite the use of the same micromagnetic model that gave good agreement for the square. While the

dynamics of a single nanomagnet should be more readily understood after eliminating the collective excitations and inhomogeneous broadening observed in arrays, the dynamics in fact remain complicated due to the non-uniform internal field. It is clear from Figure 4 that different geometries and ground states can lead to differences in precession amplitude and damping, in addition to differences in the resonant mode spectra. It has also been reported by Shaw *et al.* that the damping and linewidth of the excited modes are very sensitive to small differences in element shape (Shaw *et al.* 2009), giving further impetus to efforts to measure individual nanomagnets.

Precessional reorientation and switching

Knowledge of the spin wave spectrum of an individual nanomagnet is a prerequisite for successful precessional reorientation or switching of the magnetisation between bistable states in magnetoresistive sensor devices. As discussed in the previous section, the non-uniform static internal field and magnetisation within square nanomagnets results in a rich spin wave spectrum that depends upon the aspect ratio of the element. The excitation of a spectrum of non-uniform spin wave modes may have a negative impact on the signal-to-noise ratio of sensor devices. Keatley *et al.* used a combination of vector-resolved TRSKM and micromagnetic simulations to study the precessional reorientation of the magnetisation in a $2 \times 2 \mu\text{m}^2$ ferromagnetic square element in response to a large amplitude, in-plane pulsed magnetic field (Keatley *et al.* 2009). In Figure 5(a) TR Kerr signals of large angle reorientation are shown for three orthogonal components of the vector magnetisation that were measured simultaneously. A reorientation angle of $\sim 100^\circ$ was calculated from the in-plane (X and Y) dynamic signals (Figure 5(a)) and the saturation Kerr rotation determined from focussed hysteresis loops (not shown). Micromagnetic simulations were found to be in good qualitative agreement with the experimentally observed large angle dynamics when a Gilbert damping parameter of 0.1 was used. Figure 5(b) and (c) show the simulated magnetisation before the arrival of the pulsed magnetic field ($t = 0$) and during the pulse ($t = 1.5$ ns). The simulated images reveal that the magnetisation at the centre of the square rotates through $\sim 92^\circ$ in good agreement with the experimentally determined reorientation. However, the magnetisation along the edge of the square parallel to the bias field rotates only slightly, and acts to restore the magnetisation to the original ground state at $t = 0$. While the excitation of non-uniform spin wave modes does not seem to be significant here, the pinning of the magnetisation at the edge of the element requires the excitation field for precessional switching to be larger than that used by Keatley *et al.*. On the other hand, the excitation of spin wave modes has also been suggested as a mechanism for the enhanced damping observed for large angle magnetisation dynamics (Gerrits *et*

al. 2006). If the spin wave spectrum of an individual nanomagnet is sensitive to slight shape variations (Shaw *et al.* 2009), and if the damping is related to the excitation of the spin waves, then large angle reorientation or switching times may also be found to vary between individual nanomagnets.

Further investigation and exploitation of magnetisation dynamics

While understanding of the magnetisation dynamics of micro and nano-scale elements has advanced greatly in the past decade, many basic questions remain unresolved and new challenges continue to appear as efforts are made to devise new spintronic devices. The studies presented in the previous section have revealed that the dynamic response of an individual nanomagnet may be complicated and in poor agreement with micromagnetic simulations of ideal structures. This suggests that variations in shape and composition (McMichael *et al.* 2006) and magnetic parameters at the deep nanoscale, or even the atomic scale, must be accounted for in order to build a complete understanding of the observed resonant mode structure and damping. Polycrystalline permalloy is currently the most widely used ferromagnetic material with a damping parameter that may be as small as $\alpha = 0.008$ (Patton 1968, Twisselmann *et al.* 2003, Baberschke 2008). This has been sufficient to generate coherent effects such as spin-wave interference on the micrometer scale (Podbielski *et al.* 2006), but at least an order of magnitude reduction is required to render more features of both spintronic and magnonic technology competitive. The damping parameter determines the length scales over which spin waves can propagate, the critical current density for STT excitation (Katine *et al.* 2008, Ralph *et al.* 2008, Tserkovnyak *et al.* 2008), and the fidelity of communication and data processing devices that exploit the resonant mode spectrum. Reduced damping parameters of $\alpha=0.001$ have been realised in half-metallic materials (Mizukami *et al.* 2009), where spin-flip scattering is thought to be suppressed, while V doping has been observed to reduce the damping parameter of the highest quality Fe films (Scheck *et al.* 2007). Therefore future spintronic devices may be constructed from epitaxial thin film materials, as in the semiconductor industry today, which also provide opportunities to more fully control and exploit magnetic anisotropy.

To compete with conventional charge based electronics in future, spintronics has to function at comparable or higher frequencies. While passive spintronic devices developed for hard disk applications are able to operate at frequencies of a few GHz, there is clearly potential to extend this frequency range to tens of GHz by using materials that are subject to larger effective magnetic fields either from increased anisotropy, or through exploitation of the exchange interaction from

Ruderman-Kittel-Kasuya-Yosida (RKKY) type interlayer exchange coupling or direct exchange bias from antiferromagnets. High anisotropy materials are already beginning to be explored in STOs with perpendicular anisotropy (Mangin *et al.* 2009). Due to their small volume, devices activated by STT are susceptible to thermal fluctuations, which broaden the output of STOs and give switching processes stochastic character. While larger effective fields will promote enhanced thermal stability, increased torque will be required to activate them, compounding the need to enhance STT while minimizing dissipation. Additional strategies, such as reduction of the magnetisation or the use of assist mechanisms will therefore need to be considered. Antiferromagnetic and ferrimagnetic materials support high frequency exchange resonances (Kimel *et al.* 2004, Kimel *et al.* 2009) and their use in spintronics seems deserving of further investigation in the future.

The group velocity of spin wave excitations is very small compared to that of electromagnetic radiation. This may be construed as an advantage in minimizing cross-talk between densely packed devices, yet spin waves could alternatively prove to be a valuable mechanism for the transmission of information between or coupling of devices, particularly in the higher frequency exchange dominated regime where the group velocity begins to increase rapidly. The engineering of spin wave bands and their dispersion relations is the central aim of the emergent field of magnonics. Spintronic mechanisms will be essential for the exploitation of magnonics, providing a highly localised excitation mechanism in the form of STT and magnetoresistive readout mechanisms. An ability to couple to electromagnetic radiation is also highly desirable but is frustrated by the mismatch between the linear momentum of the photon and the magnon. At frequencies approaching the THz regime, different experimental and technical concepts such as those already known within the field of plasmonics will be required. For example, the attenuated total reflection technique has been successfully applied to studies of magnons in antiferromagnets (Abraha *et al.* 1994, Camley *et al.* 1998) but it remains an open question as to whether such techniques could be applied to ferromagnets. A higher coupling efficiency can be obtained by “wrapping” a magnonic waveguide around a microwave waveguide (Kozhanov *et al.* 2009) and recipes for producing near field microwave wave forms have been proposed even for the THz range (Kruglyak *et al.* 2005c, Kruglyak *et al.* 2007b). Antiferromagnets again provide a possible solution since they couple more easily to a THz wave, and can undergo excitation by a femtosecond optical pulse (Thiele *et al.* 2004, Weber *et al.* 2004). High frequency spin waves could then be transferred to a ferromagnet by means of interfacial exchange coupling.

The collective response of multiple spintronic devices will need to be controlled. An immediate application is in increasing the power output of STOs to a level where they can be used as agile local oscillators and perhaps ultimately for far-field microwave emission. Coherent

emission from an array of phase-locked STOs delivers power output that scales with the square of the number of individual devices, but hundreds of devices are likely to be necessary. Recently exchange coupling of four vortex oscillators has been demonstrated (Ruotolo *et al.* 2009). The vortex oscillator is attractive due to its high power output, but it is difficult to increase its frequency of operation much beyond 1 GHz. STOs supporting uniform precession continue to be of interest for higher frequency operation but the necessary coupling mechanisms remain unclear. Coupling by series circuit connection has been explored but local coupling via spin waves, dipolar interactions, or spin diffusion also offer great potential and are beginning to be explored.

Summary

This article has charted the advances in understanding of the dynamical response of thin ferromagnetic films and elements during the past two decades. During this time the field of spintronics has emerged, initially as a passive technology that enabled the development of superior sensor devices, and then as a multi-functional active technology in which the electron spin can activate processes by means of the STT. Driven by the needs of the data storage industry, dynamical response has been controlled at higher frequencies and on shorter length scales, with the concurrent development of a wide variety of new experimental techniques. Within the confines of this article only the results of TR-MOKE experiments have been explored in detail, yet they reveal that reduction of feature sizes to the nanoscale does not necessarily lead to a simplified behaviour, but yields new phenomena in which the relationship between magnetic and atomic scale structural properties becomes ever more intimate. It has been shown that scaling of passive spintronics to shorter lengthscales and higher frequencies is far from straightforward and instead demands the introduction of new materials and mechanisms. The discovery of STT has raised many additional interesting questions that will ensure that spintronics in general, and ultrafast spintronic processes in particular, will be the subject of an intense research effort for many years to come.

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Figure captions

- Figure 1. A schematic of the time-resolved scanning Kerr microscope pump-probe technique is shown. The spatial resolution of the microscope is 300 nm allowing the precessional magnetisation dynamics of ferromagnetic thin-film elements with lateral dimensions as small as 200 nm to be measured on picosecond timescales.
- Figure 2. In (a) the FFT spectra calculated from TR signals acquired from an array of square nanomagnets of different size patterned from a CoFe/NiFe(2.5 nm) film show the dependence of the mode frequency upon the element size at a bias field $|\mathbf{H}|$ of 405 Oe. For element sizes 630, 220, and 64 nm the simulated spatial distribution of the out-of-plane component of the magnetisation is shown in (b) where black and white correspond to maximum and zero amplitude respectively. The constant grey background in the images in (b) represents non-magnetic regions. After Kruglyak *et al.* 2005a.
- Figure 3. TR images of the dynamic magnetisation corresponding to three collective modes observed in an array of $80 \times 40 \text{ nm}^2$ stadium shaped elements with 40 nm edge-to-edge separation. A bias magnetic field $|\mathbf{H}_B|$ of 200 Oe was applied along the long edge of the elements. The images in the top and bottom rows correspond to the same frequency but have been extracted from measurements employing pulsed and harmonic magnetic field excitation, respectively. After Kruglyak *et al.* 2010b
- Figure 4. TR signals from single nanomagnets are shown in (a) for a square with a bias field applied along an edge and along a diagonal, and for an ellipse with a bias field along the major axis. Fast Fourier transform power spectra of the TR signals in (a) are shown as shaded line and symbol in (b). Spectra extracted from micromagnetic simulations are overlaid (bold line). In all cases the bias field $|\mathbf{H}_B|$ was ~ 200 Oe.
- Figure 5. Time- and vector-resolved signals of large angle magnetisation dynamics in a $2 \text{ }\mu\text{m}$ square element are shown in (a). The longitudinal Kerr signals (X and Y) are proportional to two orthogonal in-plane components of the magnetisation that are parallel and perpendicular to the bias field, respectively. The polar Kerr signal (Z) is proportional to the out-of-plane component of the magnetisation. Simulated images of the magnetisation are shown at time equal to 0 and 1.5 ns in (b) and (c), respectively. The grayscale represents the y -component of the magnetization M_y , where black and white corresponds to the saturation magnetization and $M_y = 0$, respectively. After Keatley *et al.* 2009

Short title for page headings

Ultrafast spintronic nanostructures

Figure 1 Keatley *et al.*

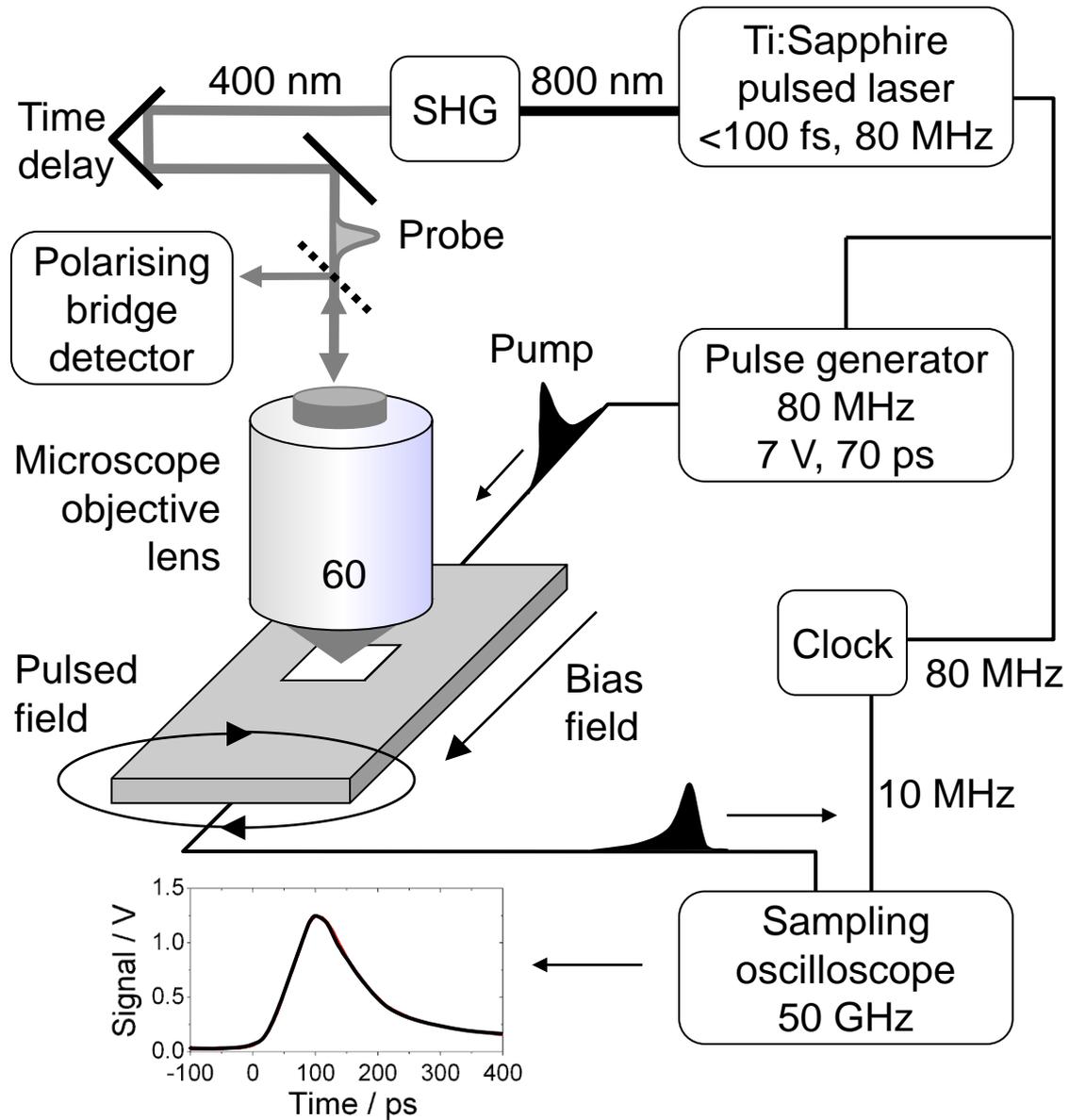


Figure 2 Keatley *et al.*

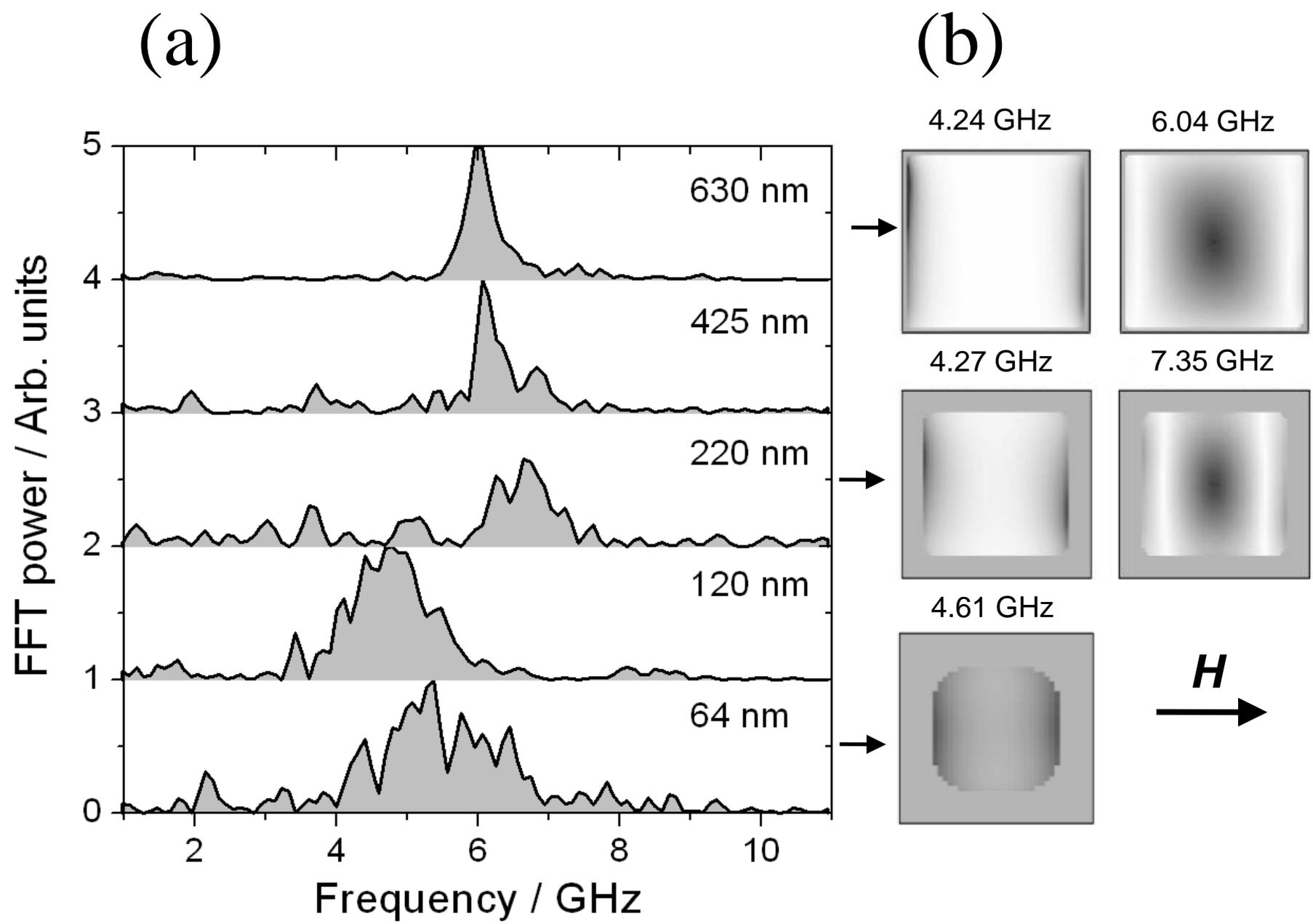


Figure 3 Keatley *et al.*

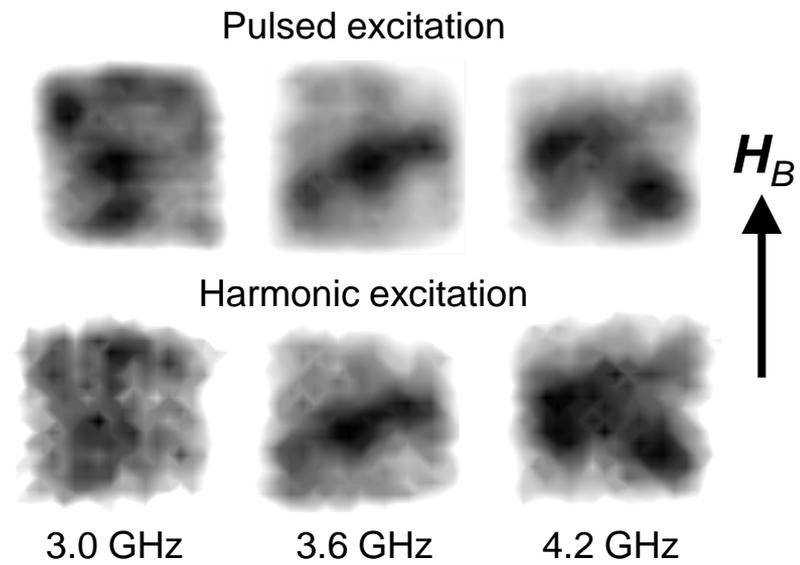


Figure 4 Keatley *et al.*

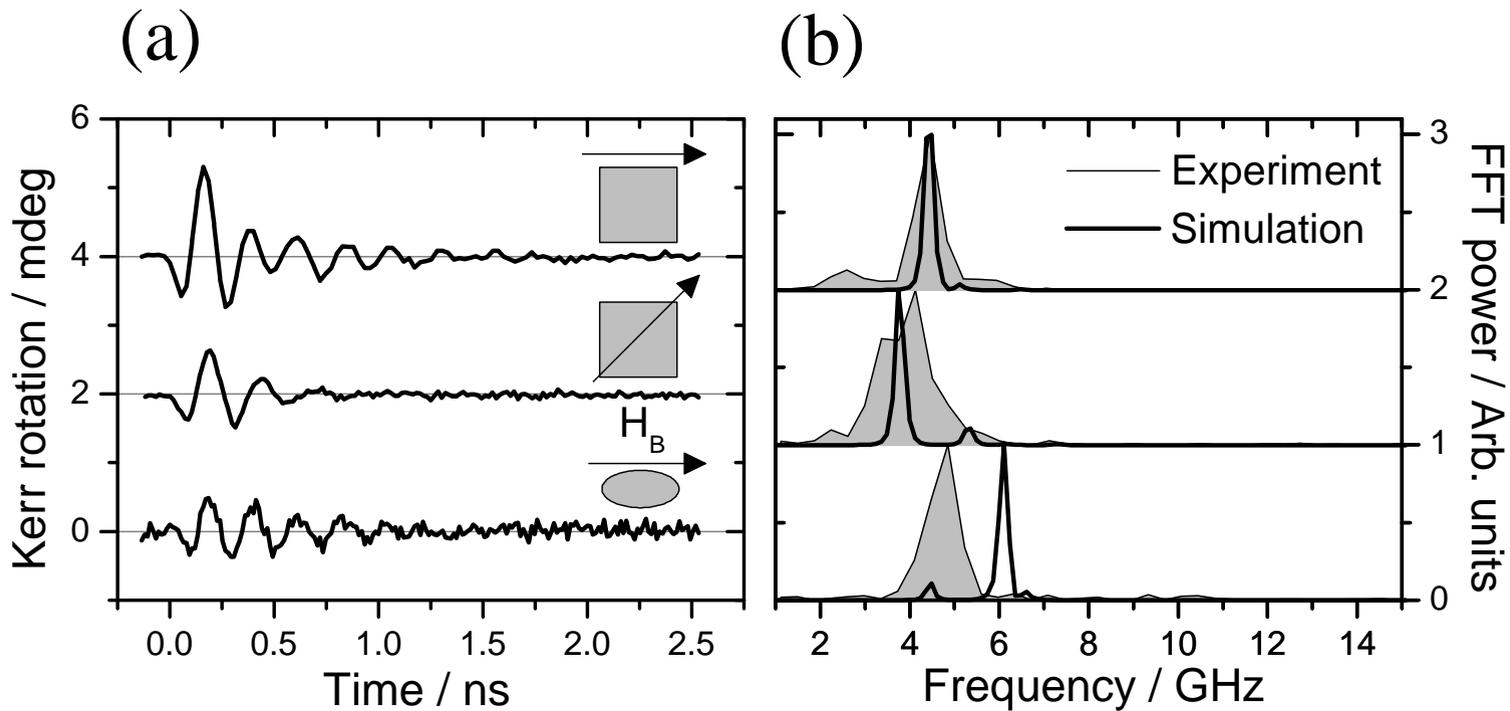


Figure 5 Keatley *et al.*

