

# Time-Resolved Magneto-Optical Investigations of Picosecond Magnetisation Dynamics in Arrays of Non- Ellipsoidal Ferromagnetic Nano-Elements

Submitted by **Paul Steven Keatley**, to the University of Exeter  
as a thesis for the degree of Doctor of Philosophy in Physics,  
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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

A handwritten signature in black ink, appearing to read 'P. Keatley', written over a horizontal dotted line.

## Abstract

In this thesis the results of magneto-optical experiments will be presented. The experiments were performed on micro-arrays of square nanomagnets in order to characterise the static and time-dependent behaviour of the nanomagnets. The static behaviour was investigated in vector-resolved scanning Kerr microscopy experiments, while the time-dependent behaviour was investigated in time-resolved scanning Kerr microscopy experiments. In the latter so-called pump-probe experiments, magnetisation dynamics were induced by exciting the sample magnetisation with a pulsed magnetic field (pump). The magnetisation dynamics were then detected using the magneto-optical polar Kerr effect (probe). The longitudinal Kerr effect was utilised in the vector-resolved scanning Kerr microscope in order to measure the in-plane components of the static magnetisation. The experimental set-up and methodology of the vector- and time-resolved scanning Kerr microscopy experiments will be discussed in detail, in particular, the detection technique that allows three components of the vector magnetisation to be measured simultaneously. Since the spatial resolution of the magneto-optical probe was insufficient to resolve the spatial character of the magnetisation dynamics within individual nanomagnets, micromagnetic simulations were used to gain insight into the character of the excited modes. Extensive testing of different micromagnetic models was carried out in order to investigate the effect of the different models on the simulated dynamics. The results of measurements carried out on the arrays of square nanomagnets revealed that the static and time-dependent behaviour of the magnetisation became more complicated as the size of the nanomagnets was reduced. In particular, similar hysteresis loops were acquired when the elements were magnetised along the uniaxial anisotropy easy and hard axes, while fast Fourier transform spectra of time-resolved signals revealed that the character of the magnetisation dynamics changed significantly as the element size and/or applied magnetic field were reduced. Interpretation of the experimental results using micromagnetic simulations revealed that the elements had a non-uniform single domain ground state magnetisation. When the field was applied along either edge of the square elements and reversed, the magnetisation was found to switch via a series of metastable non-uniform single domain states. Furthermore, the increasing non-uniformity of the single domain ground state as the element size and/or applied field were reduced lead to significant changes in the mode character excited within the elements. Comparison of

experimental spectra with simulated spectra and Fourier images of the dynamic magnetisation revealed that as the element size and/or applied field were reduced, the mode character changed from one that occupied the majority of the volume of the element, to several modes that were localised near to the edges of the element that were perpendicular to the applied field. Furthermore, deviation of the direction of the wavevector of the dynamic magnetisation from the direction of the static magnetisation was found to lead to a dynamic configurational anisotropy within nanomagnets. Following the presentation of the experimental results, the recent developments for future experimental work are presented with the aim to study precessional switching in an isolated nanomagnet. The results obtained in the experiments presented in this thesis are expected to lead to a better understanding of the non-uniform magnetisation dynamics in square nanomagnets, which have application in future magnetic data storage technologies.

*To My Parents*

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1. P.S. Keatley, V.V Kruglyak, R.J. Hicken, J.R. Childress, and J.A. Katine, *Time-resolved investigation of magnetization dynamics of arrays of non-ellipsoidal nanomagnets with a non-uniform ground state*, Submitted to Physical Review B, under revision.
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## **Declaration**

The work presented in this thesis is the result of the joint effort of many people. The contribution to this work by my colleagues is outlined below and will be acknowledged more specifically throughout the main text of this thesis. Particular contributions to this work by my PhD supervisor, Prof Rob Hicken, are difficult to describe as they permeate the whole of this thesis.

### **Chapter 1 *Introduction***

The introduction to the work presented in this thesis and the description of the motivation for conducting research in this area of physics is my own work. Details published by other authors that have been used in the discussions in Chapter 1 have been acknowledged.

### **Chapter 2 *Background principles of magnetism***

The background principles of magnetism relevant to this thesis have been compiled by myself in Chapter 2. The principles discussed in Chapter 2 are not the result of my own work. Throughout Chapter 2 the reference material used for each discussion has been acknowledged.

### **Chapter 3 *Experimental techniques***

The background principles of magneto-optics relevant to this thesis have been compiled by myself in Sections 3.2 to 3.4 of Chapter 3. However, the principles discussed in these sections are not the result of my own work. Throughout these sections the reference material used for each discussion has been acknowledged. In Sections 3.5 to 3.7 the description of the experimental techniques represents my own work. The basis for time-resolved experiments in Exeter had been set up by Prof Rob Hicken, Dr Jing Wu, Dr Ralph Wilks, Dr Anjan Barman, and Dr Volodymyr Kruglyak before I started my PhD project. The time-resolved scanning Kerr microscope (TRSKM) was set up by Dr Barman. The experiments presented in Chapter 5 were performed by myself using the TRSKM set up by Dr Barman. The experiments presented in Chapters 4, 6, 7 were performed using the TRSKM set up by myself with advice from Dr Kruglyak and Prof Hicken. Data acquisition software was written by Prof Hicken, Dr Barman, Dr Wilks and myself.

#### ***Chapter 4 Acquisition of vector hysteresis loops from microarrays of nanomagnets***

The microscale elements and microarrays of nanomagnets were fabricated by Dr Jeffrey Childress and Dr Jordan Katine at Hitachi Global Storage Technologies San Jose Research Center, California. The scanning Kerr microscope was set up by myself. The vector bridge detector was designed originally by Dr Anjan Barman. The mechanics were constructed by Mr Kevyn White and the electronics were built by Dr Barman. The original vector bridge was unsuccessful in the achieving vector sensitivity. Realignment of the quadrant photodiodes and modification of the detector electronics was carried out by myself in order to achieve vector sensitivity. The characterisation of the vector sensitivity, and the acquisition of hysteresis loops from individual microscale elements and microarrays of nanomagnets was carried out by myself.

#### ***Chapter 5 Use of microscale coplanar stripline with indium tin oxide windows in optical ferromagnetic resonance measurements***

The hybrid Au/indium tin oxide coplanar stripline was fabricated by Dr Jamie Scott and Dr Mahfuzur Rahman at the University of Glasgow. The permalloy film was fabricated by Dr Sam Ladak at the University of Exeter. The TRSKM was set up by Dr Anjan Barman. The sample was prepared by Dr Barman and myself, while measurements and data analysis were carried out by myself.

#### ***Chapter 6 Time-resolved investigation of magnetisation dynamics of arrays of non-ellipsoidal nanomagnets with a non-uniform ground state***

The microscale elements and microarrays of nanomagnets were fabricated by Dr Jeffrey Childress and Dr Jordan Katine at Hitachi Global Storage Technologies San Jose Research Center, California. The TRSKM was set-up by myself. The measurements were carried out primarily by myself with additional help from Dr Volodymyr Kruglyak. The data analysis and micromagnetic simulations were carried out by myself, except for the macrospin fitting, which was carried out by Dr Kruglyak. The parameter files used in the micromagnetic simulations were based on those originally written by Dr Kruglyak. The analysis software for micromagnetic simulations was written by Dr Evgeny Galaktionov.

## **Chapter 7 *Dynamic configurational anisotropy in nanomagnets***

The microscale elements and microarrays of nanomagnets were fabricated by Dr Jeffrey Childress and Dr Jordan Katine at Hitachi Global Storage Technologies San Jose Research Center, California. The TRSKM was set-up by myself. The time-resolved measurements were carried out by myself and Dr Volodymyr Kruglyak. The vector hysteresis loop measurements were carried out by myself. The data analysis and micromagnetic simulations were carried out by Dr Kruglyak.

## **Chapter 8 *Recent developments for future work***

The microwave probe station was designed by myself, Prof Rob Hicken, and Mr Russell Edge. The electromagnet, sample stage, and piezoelectric stage bracket for the microscope column were built by Mr Edge. Additional supports for vibration control of the sample stage were built by Mr Kevyn White. All measurements for the characterisation of the mechanical vibration were carried out by myself. The tuning of the piezoelectric stage servomechanism loop gain was carried out by myself. The new coplanar stripline was fabricated by Dr Volodymyr Kruglyak. The current pulse profiles were measured by Dr Kruglyak and Dr Andreas Neudert. Antireflective coatings (ARC) were deposited by Mr David Jarvis. Characterisation of the enhancement of the magneto-optical effect for different ARC thicknesses was carried out by myself. The microscale elements (6 or 10  $\mu\text{m}$ ) and microarrays of nanomagnets were fabricated by Dr Jeffrey Childress and Dr Jordan Katine at Hitachi Global Storage Technologies San Jose Research Center, California. The 40  $\mu\text{m}$  sized element sample was fabricated by Dr Michael Frommberger at the Center of Advanced European Studies and Research, Smart Materials Group, Germany. The new vector bridge detector was designed by myself. The mechanics were constructed by Mr White, while the electronics were built by myself. Advice on the construction of the electronics was given by Dr Charles Williams, Mr Tom Addison, and Mr Chris Forrest. Vector hysteresis loops were acquired by Mr Marco Delchini under my supervision during his summer research project in Exeter. Vector- and time-resolved measurement of images of the dynamic magnetisation of the 40  $\mu\text{m}$  element were carried out by Dr Neudert. Testing of the synchronisation of the electronic pulse generators and microwave synthesisers with the pulsed laser was carried out by Dr Neudert and Dr Kruglyak.