# Time-Resolved Imaging of Magnetisation Dynamics in Nanoscale Magnonic Structures

Submitted by **Toby Charles Davison**, to the University of Exeter
as a thesis for the degree of Doctor of Philosophy in Physics,
May 2012.



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.

……………………………

**Abstract**

In this thesis the results of several different experimental techniques are presented. Time-resolved scanning Kerr microscopy and time-resolved optically pumped scanning optical microscopy measurements were made in Exeter on bi-component anti-dot lattices and permalloy films respectively. Magnetic transmission x-ray microscopy measurements were performed on cobalt nanostructures at the Advanced Light Source at the Lawrence Berkeley National Laboratory in Berkeley, California, USA.

Time-resolved Kerr microscopy was used to study bi-component 400nm anti-dot lattices with a 1μm lattice constant. At 200 Oe the mode frequencies were obtained using time-resolved measurements. The mode frequencies of the cobalt filled anti-dots (binary sample) are 3 and 4.4 GHz. The 4.4 GHz mode has propagating character; the 3 GHz mode has non-propagating character. The mode frequencies of the air –filled anti-dot arrays (anti-dot reference sample) are 3.84 and 4.72 GHz. The 3.84 GHz mode has propagating character; the 4.72 GHz mode has non-propagating character. The alteration of the internal field by the air-filled anti-dots lowers the propagating mode frequency compared to the binary sample. Scanning Kerr microscopy was used to study the spatial character of the anti-dot modes. By fitting the spatial character the effective damping parameter(s) were determined. The effective damping parameter for the binary sample was 0.023 and 0.044 for the 4.4 and 3.04 GHz modes respectively. The 3.04GHz mode exists through the cobalt filled anti-dots leading to a high effective damping. The effective damping parameters for the anti-dot reference sample 0.026 and 0.028 for the 3.84 and 4.72 GHz modes respectively.

Time-resolved optically pumped measurements have been performed on a continuous 20nm permalloy film. This is a new experimental technique developed during my PhD. Early

data acquired on the optical microscope is compared with data measured later and attempts are made to explain the discrepancies. With a 500 Oe out-of-plane field initial time resolved signals show an oscillation at 17 GHz, the origin of the oscillation is unknown and is thought to originate from a magnon or phonon contribution. The experiment overlapping sub-micron pump and probe spots makes acquiring consistent time-resolved signals a difficult challenge. Images revealing circular lobe shapes are observed, the origin of these images is not fully understood. Later measurements are compared to the early measurements. In the recent measurements, images of spin waves with a wavelength and frequency of 2.5 μm and 4 GHz respectively are observed. These values are not reconcilable with the wavelengths and frequencies of 1μm and 17GHz seen in the images and time-resolved signals respectively. Recent measurements also revealed a strong dependence on the pump focus position on the measured images.

Lastly, magnetic transmission x-ray microscopy measurements are presented on 700nm cobalt anti-dot structures overlaid on continuous permalloy films of thicknesses ranging from 20 to 60nm. The magnetic ground states of the nanostructures are investigated using $L_3$ edge x-ray absorption and x-ray magnetic circular dichroism as a magnetic contrast mechanism. The reversal fields are determined and consistent with hysteresis loops measurements in Exeter. The dipolar fields from the complex shape of the cobalt anti-dots are expected to modulate the magnetic ground state of the permalloy. Reversal of the permalloy occurs suddenly over a consistent field window, starting and finishing between 13 ~ 17 Oe respectively. The reversal process in the cobalt occurs gradually and full saturation is not observed until fields of up to 350Oe.

**Acknowledgements**

The work presented in this Thesis is the cumulative sum of efforts from many of my colleagues, co-workers and friends. It would be unfair to say it was my own single effort and I am thankful for their much needed contribution to this Thesis and all the work that has been associated with my studies in the past few years. The list of people to thank is too long to be explicitly mentioned, minor discussions, comments and interactions on all levels with all people has in some way influenced me in one way or another to complete the work presented here. I would like to thank peers Mr Max Marcham and Mr Tom Duckworth from the Magnetic materials group. They have been there since I, having started at the same time and are my closest associates and friends within the group, who always brightened a situation with unforgettable humour. They were always available as a sounding board for my frustrations and worries, and were always available for playing football and 'walks around the pitches'. On an experimental basis, I would like to thank Dr. Yat-Yin Au who designed much of the experimental apparatus I used and his much needed guidance on matters experimental and practical. The School of Physics workshop has been an invaluable asset for experimental work, being able to advise, mill and drill apparatus into working order, namely I would like to thank Matt Wears and Russell Edge for their help and guidance on all matters practical and mechanical. Their common sense approach to practical work was a refreshing insight that remained useful and carried over to my experimental work in the lab. I would also like to thank and acknowledge the School of Physics and the rest of the magnetic materials group for their encouragement and help over the years. Last but not least, I would like to thank my supervisor Dr. Volodymyr Kruglyak, who always had valuable insight to my experiments and whose persistence and supervision has led me to this point here.

*List of Contents*

***List of Publications***

1. Y. Au, T. Davison, E. Ahmad, P. S. Keatley, R. J. Hicken, and V. V. Kruglyak, *Excitation of propagating spin waves with global uniform microwave fields***,** Applied Physics Letters **98**, 122506 (2011)
2. Y. Au, E. Ahmad, O. Dmytriiev, M. Dvornik, T. Davison, and V. V. Kruglyak, *Resonant microwave-to-spin-wave transducer,* Applied Physics Letters, **100**, 182404 (2012)

*List of Figures*

***List of Tables***

***Declaration***

The work presented in this thesis is the joint effort of many people. The contribution to the work is outlined below and is also done so throughout the main text of this thesis.

**Chapter 1 – Introduction**

The introduction to the work in this thesis, the brief history of magnetism and the outline of research is my own. Details published by authors from the literature used in this chapter has been acknowledged.

**Chapter 2 – Background Theory**

The material in the background theory chapter has been compiled by myself. The concepts and principles presented in chapter 2 are not the result of my work. The reference material used in chapter 2 has been acknowledged.

**Chapter 3 - Experimental Setup and Development**

The experimental design of the field-pumped time-resolved Kerr microscope is due to Prof. Rob Hicken, Dr. Paul Keatley, and Dr. Volodymyr Kruglyak. The refinement of the drawings and assembly of the time-resolved Kerr microscope was performed by Dr. Yat-Yin Au. The experimental design of the time-resolved optically pumped scanning optical microscope is due to Dr. Volodymyr Kruglyak, with the construction drawing produced by Dr. Yat-Yin Au. Assembly of the time-resolved optically pumped scanning optical microscope was performed by myself and Dr. Yat-Yin Au.

Machining of part for both microscopes was performed by Mr. Russell Edge in the machine workshop in Exeter. The alignment and maintenance of the shared optics and optomechanics beyond the microscopy probe stations was performed by myself with assistance of Dr. Thomas Isaac, Dr. Yat-Yin Au, Mr. Rostislav Mikhaylovskiy, and Dr. Mykola Dvornik. The software for data acquisition for both experiments was written by Dr. Yat-Yin Au and Dr. Mykola Dvornik.

**Chapter 4 - Time-Resolved Scanning Kerr Microscopy measurements of Cobalt and Air filled Anti-dot structures**

The electrically connected two-dimensional Co- and air-filled anti-dot lattices for the time-resolved scanning Kerr microscopy measurements in Exeter were designed and fabricated by Mr. Georg Dürr from the Technical University of Munich and Marco Madami from the University of Perugia, who (with their colleagues) have also performed their preliminary characterization using Vector Network Analyser Ferromagnetic Resonance and Brillouin Light Scattering measurements and micromagnetic simulations. I was taught how to use and operate the Kerr microscope by Dr. Yat-Yin Au. Data presented in this thesis from experiments on the binary and air-filled anti-dot lattices using the time-resolved scanning Kerr microscope were acquired by myself.

**Chapter 5: Time-resolved Optically pumped Scanning Optical Microscope measurements of a Permalloy film**

The 20nm thick continuous permalloy film was fabricated by Dr. Ehsan Ahmad in Exeter. Data presented in this thesis from experiments on the permalloy film using the time-resolved optically pumped scanning optical microscope were acquired by myself.

## Chapter 6: Magnetic Transmission X-ray Microscopy (M-TXM) of Cobalt Nano-structures

The cobalt/permalloy nanostructures measured at the Advanced Light Source in California were fabricated in Exeter by Dr. Ehsan Ahmad. The measurements were possible thanks to beam line scientist Dr. Peter Fischer and beam line postdoc Dr. Mi-Young Im. I am grateful to Dr. Mi-Young Im for showing us how to operate parts of the microscope. Data on the beam line were collected by myself and Dr. Mykola Dvornik from Exeter and Mr. Michal Mruczkiewicz from the Adam Mickiewicz University in Poznan, Poland. The software for image analysis was written by Dr. Mykola Dvornik. The data analyses were performed by myself.