TITLE: Micromagnetic calculation of spin wave propagation for magneto-logic devices

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Abstract

The propagation of magnetic wave packets in magnetic nanowires was calculated as function of wire width, exchange constant, field strength, field ramp time, field area size and geometry of a magnetic nanowire. Spin waves are excited locally by applying a small perturbation in the magnetization in a 20 nm wide region. A wave packet is emitted from the input region and travels along the wire with a velocity of 740 m/s. The finite element micromagnetic simulations show that wave packets can be guided along a bent nano-structure without losses due to geometry; amplitude and frequency are exactly the same as in a straight wire with equal distance between excitation point and probe. The wave amplitude was found to decrease with increasing rise time of the excitation field with an upper limit of 100 ps. For a permalloy wire with a thickness of 10 nm, the frequency peak changes from 10 GHz in a wire with 60 nm width to 6 GHz in a wire with 140 nm width.

Introduction

Logic operations using spin waves in magnetic nanostructures were proposed recently [1, -5]. Development of spin wave based magnetic devices requires a basic understanding of spin wave propagation and spin wave decay in magnetic waveguides that will make up the building blocks of future logic devices. Different designs for spin wave based information transportation and information processing were suggested.

Khitun [1] proposed a cell based computational architecture in which information is carried via spin wave propagation between nanoscale bistable logic cells. The spin waves are supported within a CoFe film placed below a two-dimensional array of nano-cells. The cells interact via the inductive coupling produced by spin waves propagating in a ferromagnetic film. The elementary cells are built by a pair of vertically-aligned resonant tunnelling diodes that are connected in series and inductively coupled with a ferromagnetic film. By using spin wave properties such as spin wave superposition and spin wave attenuation, information processing can be achieved .

Several groups discuss spin wave interferometers [2-5]. In Mach-Zender-type logic elements a spin wave is split into two branches. Within one branch a phase shift may be induced by a local field, a domain wall, or a change in magnetic properties of the waveguide. Constructive or destructive interference is then used to perform logic operations. Such a device was demonstrated using YIG based macroscopic microwave waveguides [2]. Alternatively, waveguides made of permalloy may be utilized to shrink the size of the device to several micrometers [2]. Micromagnetic simulations show that spin waves may travel in magnetic nanowire structures [4-5]. The spin waves are confined laterally by the width of the magnetic nanowire. The functional behaviour of logic devices using magnetic nano-wires was investigated using micromagnetic simulations: Hertel and co-workers demonstrated such a Mach-Zender-type interferometer [4] where the phase shift in one branch is induced by a magnetic domain wall. Choi and co-workers [5] showed spin wave interference at a double slit realized by a nanostructured permalloy film.

The advantage of nanowire networks as building blocks for spin wave logic devices as compared to conventional YIG based microwave waveguides is the small size of the devices. However, in order to achieve a fully functional device write and read out has to be realized on a nano-scale. Therefore we propose to combine resonant tunnel diodes [1] for spin wave amplification and the read out of spin wave states with nanowire networks for logical operations and well defined information transport. Spin wave packets may be generated by an applied field generated locally with a current carrying nanowire. In order to realize such a device the basic properties of spin wave propagation in magnetic nanowires has to be understood. In this paper we investigate spin wave propagation in narrow-width permalloy nanowires. It is crucial to understand the influence that different wire characteristics have on the propagation of spin waves so that we can predict accurately that our devices will work as intended. Thus we provide here a number of tests that form an overview of characterisation.

Method

We use the hybrid finite element (FE) boundary element (BE) method to perform a series of numerical micromagnetics calculations [6]. A rectangular stripe $Ni_{80}Fe_{20}$ nanowire (Fig. 1) is used, which includes boundary conditions of increased Gilbert damping constant, α, at each end to limit reflections from spin-waves [7-8]. The total length of the wire is 1000nm, with a standard width of 100nm and thickness 10nm. The finite element mesh size is kept at 5nm. Standard material parameters for the NiFe Permalloy are used, with exchange constant $A = 1.3 \times 10^{-11}$ J/m, Gilbert damping constant $\alpha = 0.02$, saturation magnetization $J_s = 1.0$ T and zero magnetocrystalline anisotropy.

One-dimensional spin waves are excited locally by applying a small perturbation in the magnetization in a 20 nm wide region at the centre of the wire. This is usually achieved with a focused magnetic field that is ramped from zero to 0.1 T in 10 picoseconds and remains constant thereafter. The wire is initially magnetized along the *x*-orientation, as determined by the shape anisotropy of the wire geometry. The applied field is *y*-orientated. Spin waves propagate away from the perturbed region in both directions along the long axis of the wire.

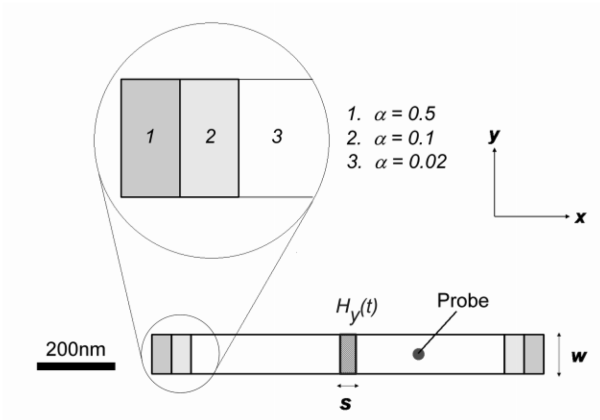

Figure 1 - Schematic of the permalloy stripe nanowire used during our tests. The total length of the wire, which lies in the x-y plane, is 1000nm. The wire is 10nm thick. The end regions have a stepped, increased Gilbert damping constant in order to reduce spin-wave reflections from the ends of the wire. The width of the wire, *w*, is altered during one experiment to test the effect of wire geometry on the spin-waves. The size of the area of focus of the applied magnetic field, *s*, is also altered in a separate test to check its respective influence.

The spin-waves are measured using a probe point positioned 180nm from the centre of the wire. At the probe point the magnetization component perpendicular to the wire's long axis is recorded as a function of time. The recording signal $M_{\_normal}(t)$ is then analyzed in the time domain or Fourier transformed to perform a comparison of different wire characteristics in the frequency domain.

To measure the influence of nanowire geometry on the spin-waves, the width of the wire, *w*, is altered incrementally between 60 and 140 nm while the other dimensions remain constant. To measure the influence of the area over which the local field is applied, the length of wire over which it is applied, *s*, is altered incrementally between 10 and 50 nm while all other dimensions and the field strength remain constant. To assess the influence of field strength, the strength of the applied field is altered incrementally between 0.025 T and 0.4 T while keeping all other parameters constant. To see the effect of changing exchange constant, *A*, in the wire it is altered between 0.3×10^{-11} Jm^{-1} and 2.3×10^{-11} Jm^{-1}. In a separate test, the rise time of the ramped applied field is altered between 25 ps and 100 ps while keeping all other parameters constant.

To measure spin-wave velocity we introduce a second probe point at a known distance away from the first probe. The arrival time of the maximum peak in the spin-wave packet can be used to calculate the approximate velocity of the packet.

To test for spin-wave propagation around a curved geometry a curved nanowire is constructed with a 90° bend. A straight wire is also constructed for comparison, and a probe is used to measure the local magnetization away from the orientation of the wire easy axis. In both cases we probe the magnetization component perpendicular to the wire to analyse the spin wave propagation.

Results

Spin-waves are emitted in both directions from the region where the focussed field is applied, and travel along the wire with a velocity of approximately 740 m/s. Because the field is switched on almost instantaneously (the ramp time is quite short with respect to the length-scale of the experiment) the perturbation causes a packet of waves to be emitted. The process of spin wave excitation is discussed in more detail later. The reminder of the results section is organized as follows. First we report spin wave propagation through curved nanowire structures. Then we discuss the influence of the excitation field, the intrinsic magnetic properties, and the wire characteristics on spin wave creation and propagation.

In the curved wire, the spin-waves are guided around the bend without losses due to geometry (Fig. 2). The results obtained for a straight wire (Fig. 1) were compared with the results obtained for the bent structure (Fig. 2). The wave measured after a certain distance from the excitation point is independent of the wire's curvature; amplitude and frequency at the probe point are comparable to the case of a straight wire with equal distance between excitation point and probe. Note that the probe measures M_x in the curved wire as opposed to M_y, to account for the 90° angle. The spin wave propagation through the bent structure is illustrated in Fig 2. The images are recorded at different times after the excitation. The greyscale maps the out of plane component of the magnetization. Fig 2c also shows the magnetization at the probe point, $M_{\_normal}(t)$, as a function of time. Fig 2d shows the Fourier transform of $M_{\_normal}(t)$ for the bent structure and the straight wire. The spin wave frequency as well as the spin wave amplitude are similar for both cases. This result is somewhat surprising since we would expect some reflection or dispersion of spin waves from the curve, but we conclude that any interference from such features is minimal owing to the smooth shape of the curve.

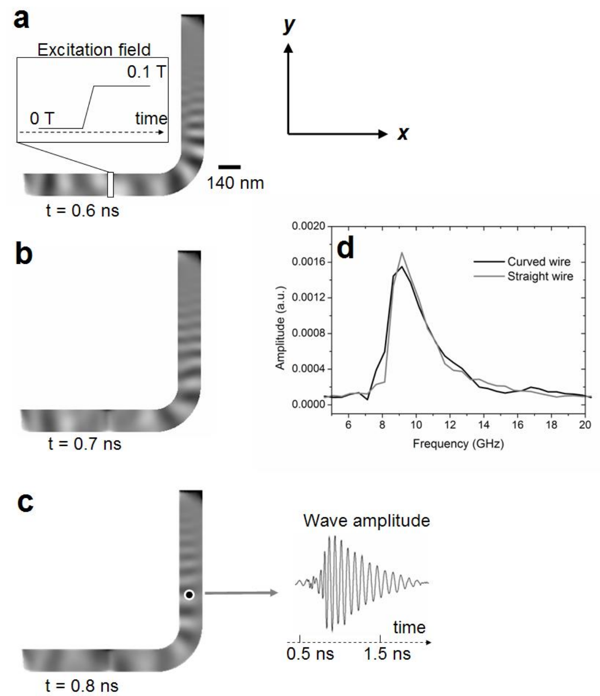

Figure 2 - (a)-(c) Images showing the magnetization configuration in the curved nanowire at respective times after the external field is applied. Dark areas indicate magnetization in the *x*-direction and light areas in the *y*-orientation. In (c) the waveform of the spin wave packet as seen at the probe is given in a temporal plot. In (d) the frequency amplitude of the spin-waves at the probe are given for the curved and straight wires and show no change in position of the frequency peak as well as no change in amplitude.

The spin wave is excited with a focussed magnetic field that is ramped from zero to 0.1 T in 10 picoseconds and remains constant thereafter. The wave amplitude was found to decrease with increasing rise time of the excitation field with an upper limit of 100 ps (Figure 3). The closer the field profile was to an ideal step function, the higher was the induced spin wave amplitude. This is because a change in the external field induces a torque on the magnetic moments, which precess around the field vector until damping causes them to align parallel with it. A more sudden or more extreme realignment of the field induces a larger torque on the magnetization vector, meaning larger precession amplitudes. It is this precession that propagates along the wire through the exchange interaction and disruptions in the demagnetizing field. In comparison, realigning the field very slowly induces a relatively small torque, and the magnetization is soon able to align with the field due to damping. In this situation any spin wave generation is minimal in amplitude.

A field change faster than the intrinsic relaxation time of the nanowire magnetization will put the system out of equilibrium. The magnetization will relax back to its new equilibrium state by gyromagnetic precession in a confined region that emits a spin wave packet. The magnetization in the excitation region acts as a local microwave source over a well defined period of time. In the excitation regions the magnetization precesses with decreasing amplitude. At a time of 0.5 ns after the excitation field reached its maximum, the precessional motion stops to due damping. Thus the proposed method of locally ramping an excitation field introduces a spin wave packet into the magnetic nanowire. In further investigations we varied the size of the excitation region in the range from s = 10 nm to s = 50 nm. The results showed that the size of the area where the focussed field is applied does not affect the frequency of the emitted spin-waves.

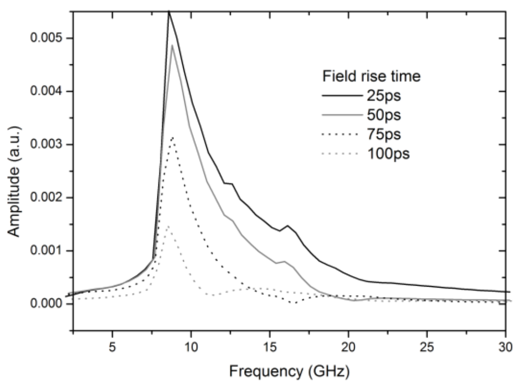

Figure 3 – Fourier transform of the perpendicular magnetization component at the probe point. The field rise time is altered. A faster rise time introduces a larger amount of energy into the system, resulting in spin-waves of greater amplitude. However, spin-wave frequency is unchanged.

If the strength of the applied field is increased then the amplitude of the generated spin waves also increases (Fig. 4). For larger field strengths the higher harmonic frequencies of the system are observed at 12GHz and 16GHz, as is the case with any such system that is being strongly driven. These higher harmonic features are also seen in the data for the field rise time experiment where rise time is short, approaching a step function (Fig. 3). For our wire dimensions, field strengths any higher than 0.1 T introduce a large amount of distortion to the frequency spectrum of the spin waves.

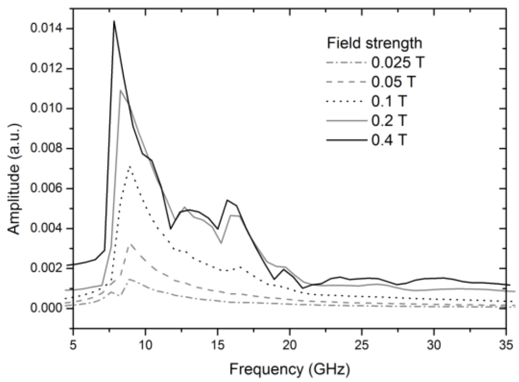

Figure 4 - Fourier transform of the perpendicular magnetization component at the probe point for different field strengths. Larger field strengths result in multiple peaks in the frequency plot, due to highly non-uniform magnetic states at the source region.

For the permalloy wire with a thickness of 10 nm thickness, the peak frequency changes from 10 GHz in wire with 60 nm width to 6 GHz in a wire with 140 nm width (Fig. 5). The accompanying increase in spin wave amplitude is a result of the corresponding increase in the area of the wire that is submitted to the external field as the wire width becomes larger.

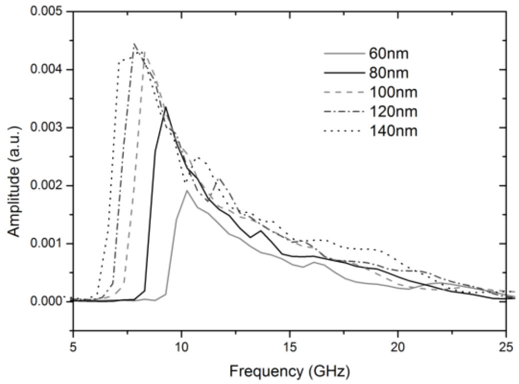

Figure 5 - Wire width, *d*, is modified. An increase in d results in a downward shift of the frequency peak. Any increase in spin-wave amplitude is down to the corresponding increase in the area of the wire that experiences the localised applied field.

The exchange constant of magnetic thin films or patterned thin film structures may be significantly different from the exchange constant in bulk magnets [9, 10]. Therefore it is important to know the effect of strength of exchange on the spin wave properties. For low exchange constant, *A*, the spin-waves do not behave in a coherent manner and the frequency of the wave packet does not have a single clear peak (Fig. 6). As *A* is increased the spin-waves become more coherent and form a single frequency peak.

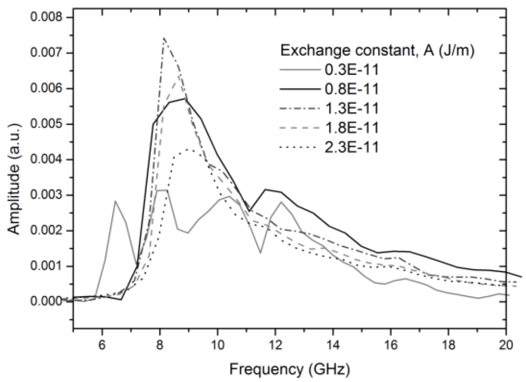

Figure 6 - Exchange constant *A* in the NiFe nanowire is modified. For lower exchange constants the spin-waves are less coherent, but as it increases they form a single frequency peak.

Conclusions

We proposed techniques to induce spin wave packages into magnetic nanowires by exciting gyromagnetic precession in a locally and temporally confined region. The properties of spin wave packets were investigated for different nanowire characteristics using micromagnetic modelling techniques. One exciting result is that the spin wave packet propagates along a curved magnetic nanowire without any losses induced by the nanowire shape. The frequency of the induced spin waves can be tuned by changing the width of the nanowire in the range from 10 GHz (60 nm wide wire) to 6 GHz (140 nm wide wire). In addition to the geometry, intrinsic properties like the material parameters of the wire were found to be important. In order to obtain well defined wave packets the nanowire should have an effective exchange constant of at least 8 pJ/m.

The wave packets propagate across several micrometers when the intrinsic Gilbert damping constant is sufficiently small ($\alpha < 0.05$). Quantitative simulations on the attenuation of spin waves in magnetic nanowires as function of surface roughness will be published elsewhere.

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