Spin wave propagation in ferromagnetic wires with an arbitrary field direction

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Abstract. We report on the measurements of quantized spin waves spectra in thin ferromagnetic wires with an arbitrary field orientation obtained by using an original micro antenna configuration. The high efficiency of energy transfer from the micro antenna to the magnetic wires allows us fabricating devices using remanent magnetization configuration

1. Introduction
Spin wave propagation in ferromagnetic films has been used for a long time to produce RF devices. However, all these devices are made with garnet type films due to the extremely low spin wave absorption in these materials [1]. The development of devices using metallic films would open the way for low cost integrated RF devices like agile attenuators, circulators etc. Unfortunately, the spin wave attenuation in metallic films is large and practical devices should have tens of µm lengths. Several years ago, a technique based on micro-antennas has been introduced [2] which has allowed exciting and propagating spin wave in permalloy stripes with a reasonable efficiency when the magnetization is perpendicular to the stripes. When the magnetization is along the stripe, conventional geometry of micro-antennas cannot be used because the excitation field is along the magnetization. In ref [3], the authors have used a end of microantenna to create a transverse excitation field with a rather low efficiency. In our approach we have simply used microantennas at 45° from the stripe direction. This allows us exciting efficiently spin waves for any planar orientation of the magnetization. In this paper, after a small introduction on quantized spin waves, we describe the experimental system and we give the results obtained for different magnetization orientations and in particular at 45°.

2. Spin wave modes in confined stripes
Spin waves in confined stripes have been extensively studied by different experimental techniques like ferromagnetic resonance, Brillouin Light scattering and microantennas. A number of model have been developed when the stripe magnetization is homogeneous [4], [5], or in non saturated systems [6]. When a field is applied the frequency of the spin waves is increasing typically as \( \sqrt{M_s(H + M_s)} \) where \( H \) is the applied field and \( M_s \) the magnetization of the film at saturation. The confinement induces a quantization of spin waves and for stripe width below 20µm different modes can be clearly separated. Figure 1 shows an example of resonance spectrum of two 5µm lines separated by 5µm measured with a microantenna.
The dispersion of the spin waves as function of their wavevector (k) can be measured with BLS [7], [8] and show quantized k values for each mode.

3. Sample fabrication and characterization

Our samples are made of three layers deposited on glass substrate: Ferromagnetic system, Insulator layer, microantennas. The ferromagnetic material used in our samples is permalloy. First a full plane layer of 45nm deposited by RF sputtering at 3nm.min\(^{-1}\) rate is lifted off. Magneto-Optic Kerr effect measurements reveal a coercive field of 0.2mT and ferromagnetic resonance shows a saturation magnetization of 0.93T. The samples presented here have two Py lines of 6µm width separated by a 6µm space. The insulating layer is a full plane silicon nitride film. It is deposited on the pre-etched and patterned Py by sputtering at 65nm.min\(^{-1}\) rate. Finally, antennas are produced by lifting off a bilayer of titanium (9nm)/gold (90nm)
4. Microantenna properties and setup

The simplest microantenna is two parallel stripe lines shortened at the end. All the structure of a sample can be seen in top view in figure 2. On the electronic point of view, the antenna can be modeled by a resistance and inductance in series. The typical resistance of our antenna is 22 Ohms. These antennas are connected to picoprobes for signal injection and detection.

On a spin wave point of view, the microantenna is a field producer at an arbitrary frequency but a spatial shape determined by the dimensions of the antenna. Figure 3 shows the direction of the created magnetic field and the intensity of the excitation field as function of the $k$ vector.

![Microantenna diagram](image1)

![Field intensity](image2)

**Figure 3.** View of the created fields (left), intensity of the field in $k$ space (right).

The effective efficiency of the antenna is hence dependant on the possible spatial waves which can be excited. The intensity of the field created by the antenna is rather large, typically 5mT for a 0dbm RF power. The detection antenna has exactly the same properties than the excitation one. Hence the selectivity in $k$ space for the complete device is just proportional to the intensity given in fig 3.

P. Emtage has developed the theory of the coupling between a spin wave and a current. That theory can be applied to calculate the effective efficiency of the complete device owing the knowledge of the damping parameter of the spin wave. This calculation has been done for the case of MsFVW (Magnetostatic Forward Volume Waves), MsSW (Magnetostatic Surface Volume Waves) and MsBVW (Magnetostatic Backward Volume Waves) [9] [10].

5. Experimental results

We present some results which show the good efficiency of the excitation and detection for three orientations of the magnetization of the stripe. The device is a pair of microantennas separated by 20µm and linked by only two 6µm wide stripes of permalloy. $0^\circ$ is along the stripe (MsBVW). For $90^\circ$ (MsSW), we see that the frequency is first decreasing as function of field. This is due to the rotation of the magnetization [11],[12]. At 20 mT the center of the stripe is perpendicular to the field and the frequency increases with the field. At $0^\circ$ there is no rotation and the frequency is increasing with field as waited. For $45^\circ$, the rotation effect can be seen at very small fields. The ratio of intensities between $0^\circ$ (or $90^\circ$) and $45^\circ$ is 2, due to geometrical reasons.
6. Conclusions
We have shown that spin waves can be reasonably excited and detected in micrometric metallic stripes even in their remanent state by 45° microantennas. This is the first step for the building of efficient integrated agile devices working without any external field. In particular that configuration can be used for the realization of micro-spin wave interferometers.

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