Transmission of GHz spin waves through periodically nanopatterned ferromagnets

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Abstract

We have coupled electromagnetic waves in the GHz frequency regime to collective spin excitations in ferromagnetic thin films which are periodically patterned on the nanoscale. For this we use pairs of micro- and nanostructured coplanar waveguides (CPWs) connected to a vector network analyzer. In a short period antidot lattice we find spin-wave propagation between two collinear CPWs with velocities of up to several km/s. Our findings open novel perspectives for nanostructured magnonic devices and magnetic metamaterials offering fast processing of GHz signals.

1. Introduction

In recent years metamaterials have attracted a lot of attention and are of great interest both technologically and scientifically. Metamaterials consisting of non-magnetic dielectric materials and/or metals have already been shown to exhibit dynamic properties which are not known from natural materials, i.e., a band structure with artificially tailored allowed minibands and forbidden frequency gaps or a negative refractive index. [1] Such properties are provoked by periodic nanopatterning on length scales which are commensurable with or shorter than the wave length of the relevant electromagnetic (e-m) wave in the microwave or optical frequency regime. Magnetic materials offer the perspective to couple e-m waves, which might be of a wave length of 10^{-2} m in the GHz frequency regime, to magnonic excitations, i.e., spin waves (SWs). Relevant SWs have a wave length as small as about 10^{-7} m = 100 nm at the same frequency. Periodicities of artificially tailored metamaterials can thus be made orders of magnitude smaller if magnetic materials are used. This allows a significant miniaturization of microwave components which make use of metamaterial characteristics to manipulate and control wave properties. Recent work focused on periodically patterned magnets such as antidot lattices (ADLs) [2], nanowire arrays [3,4] and, more visionary, protein-crystallized 3D structures [5].

We have studied ADLs and measured the scattering parameters between two collinear waveguides (CPWs) which are integrated to thin $Ni_{80}Fe_{20}$ films with periodic arrays of holes arranged on a square lattice. We observe standing and in particular propagating spin waves. Investigating different magnetic ADLs we find both magnonic crystal behavior and signatures which suggest metamaterials properties for spin waves [6]. The relevant magnetic devices incorporate 120 nm diameter holes. The periods p range from 300 to 4000 nm. In this paper we report an experimental investigation on an ADL with p = 300 nm. The periodic array of nanoscale holes modifies significantly the dynamic response of the ferromagnet. We find in particular fast SW propagation induced by the dynamic coupling of localized SW excitations.

2. Experimental Setup and Broadband Spectroscopy

A microwave probe station is employed to measure spin-wave generated voltages in CPWs integrated to magnonic devices. A vector network analyzer (VNA) with two ports creates a sinusoidal microwave signal and detects e-m waves in reflection and transmission configuration. The typical microwave rf

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output power is 1 mW to stay in the linear regime [7]. CPWs are fabricated using a trilayer consisting of evaporated Cr, Ag and Au (from bottom to top layer). We perform lift-off processing making use of either photo or electron-beam resist masks. The CPWs are integrated to about 25 nm thick $Ni_{80}Fe_{20}$ (permalloy) where periodic square lattices of holes have been patterned using focussed ion beam etching [Fig. 1]. The holes have a diameter of 120 nm. The permalloy has been deposited on a gallium arsenide substrate using lift-off processing and covered by a silicon oxide layer. We use two collinear CPWs to study SWs propagating through such antidot lattices. The separation between the inner conductors is smaller than the decay length of the SWs amounting to about 20 µm in our case. Microwave probe tips are used to contact the CPWs. A static magnetic field *H* with values up to 100 mT is generated by two pairs of current coils and two pole shoes [8]. This setup allows us to control the orientation of the in-plane field *H*. The spectrometer setup is protected against environmental noise by a shock absorbing table and by a laminar flow box with soft-PVC curtains to reduce the number of dust particles and air draft.

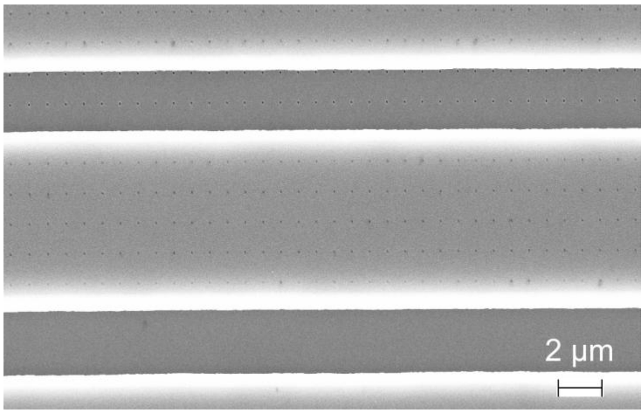

Fig. 1: Scanning electron microscopy picture showing a coplanar wave guide (bright color) on top of a permalloy film (dark) where parts of the film are patterned with a periodic array of holes. Their diameter amounts to 120 nm.

In Fig. 2 we show SW spectroscopy data obtained on an ADL with a period *p* of 300 nm. When studying SW excitations in reflection configuration on a single CPW, i.e., the emitter CPW [Fig. 2(a)], we find several modes with different eigenfrequencies. They are between 2 and 11 GHz. The modes are anisotropic and vary with the in-plane orientation of *H* as expected from earlier studies on ADLs with larger *p* [9]. For $\eta = 0$ we find a pronounced mode at 2.5 GHz. It can be shown by micromagnetic simulations [6,10] that this mode reflects the excitation of a so-called edge mode. On ADLs with large *p* it has been reported that this excitation is a localized mode and resides in a deep potential well formed by the inhomogeneous internal magnetic field. The relevant inhomogeneity which creates the confinement is induced by the stray field around each hole. In Fig. 2(b) we find that pronounced SW propagation between emitter and detector CPWs is found for this mode only. We attribute this to dynamical coupling between the localized edge modes. This has recently been substantiated by micromagnetic simulations (not shown) [6,10]. In particular, an allowed miniband is formed across the ADL supporting SW propagation. When we evaluate the SW propagation velocity *v* we find values of up to 6 km/s at 40 mT. This value holds in the long wavelength limit, where the wavelength of the SW is much larger than the period *p*. The miniband and SW propagation are found to be controlled by the orientation of *H*. This is seen in Fig. 2 (b) where propagation is found only for small angles η. Here, the spatial separation between edge modes at neighbouring holes is expected to be smallest following the micromagnetic simulations. For large η the separation is increased. As a consequence the dynamic coupling is reduced such that the miniband formation does not take place. SW propagation is suppressed.

In conclusion we have reported spin-wave spectroscopy on a periodic array of nanoholes etched into a thin film of permalloy. We find relatively fast propagation velocities of SWs of 6 km/s. This is due to an allowed miniband formed via the periodic patterning on the 300 nm lateral length scale. The metamaterials properties are controlled by an external means, i.e., the magnetic field. This offers new perspectives for nanoscale microwave components.

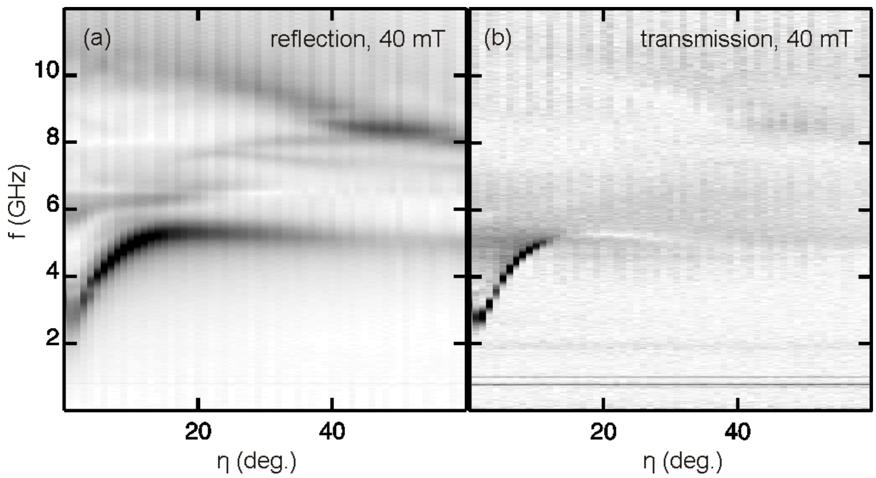

Fig. 2: (a) Spectra measured on an emitter CPW in reflection configuration. Dark color indicates spin wave resonances in the underlying antidot lattice consiting of 120 nm diameter holes arranged on a square lattice with a period of 300 nm. (b) Spectra measured in transmission configuration between the emitter and detector CPW. Black indicates propagation of spin waves between emitter and detector CPW. The separation between the 2 µm wide inner conductors is 12 µm. We have varied the orientation of the in-plane magnetic field of 40 mT. The angle η is defined with respect to the inner conductor of the CPW. We find a strong propagation signal for the lowest-frequency mode in a small angular regime.

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