Microwave Antennas for Broadband Spectroscopy on Magnonic Metamaterials

T. Schwarze[1], R. Huber[1], G. Dürr[1], F. Brandl[1], S. Neusser[1], K. Thurner[1], and D. Grundler[1]

[1]Lehrstuhl fuer Physik funktionaler Schichtsysteme, Physik Department E10, Technische Universität München, James-Franck-Str. 1, D-85748 Garching b. Muenchen, Germany; Fax: + 49 8928912414; email: dirk.grundler@ph.tum.de

Abstract

We report on a technique allowing us to explore magnonic metamaterials by all electrical broadband spectroscopy. The spectrometer setup and, in particular, different designs of tailored microwave antennas are presented. We show microwave devices which allow us to address both, magnonic crystals and magnonic metamaterials by covering different wave-length regimes. The antennas are operated at frequencies of several GHz to excite the ferromagnetic materials at wave vectors comparable to inelastic light scattering experiments.

1. Introduction

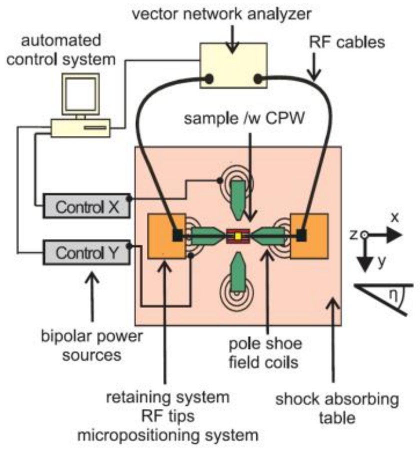
In recent years metamaterials have attracted a lot of attention and are of great interest both technologically and scientifically. Photonic metamaterials are periodically patterned materials created to shape and manipulate the flow of light, or more general of electromagnetic (e-m) waves. Magnetic materials 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). For them, the wave length is as small as about 10^{-7} m = 100 nm at the same frequency. As a consequence, periodicities of artificially tailored metamaterials can be made orders of magnitude smaller. 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 materials such as antidot lattices [1], nanowire arrays [2,3] and, more visionary, protein-based 3D structures [4]. In this paper we report micro- and nanopatterned microwave antennas designed to couple e-m waves into magnonic metamaterials in different wave length regimes. The rf current $\mathbf{I_1}$ through an antenna 1 excites a magnon via the torque $\boldsymbol{M}$ *x* h, where $\boldsymbol{M}$ (h) is the magnetization (rf magnetic field). The voltage [5] $V_2 = i\mathrm{I}_1\omega \cdot \frac{2\pi\mu_0 t_s l \chi_{tot}(\omega')\delta(\omega-\omega')\cos(\eta)}{w_1 w_2} \times \int \mathrm{d}y \left(h_{y0,2}(y) h_{y0,1}(y)\right)$ is detected by a further waveguide 2. Here, $\chi_{tot}(\omega')$ is the total susceptibility of the material given by all contributing wave vectors k that are excited, l is the length of the inner conductor of the coplanar waveguide (CPW) along the x direction, t_s is the thickness of the magnetic material, $\rho(\omega)$ is the excitation efficiency for a given k, and η is the angle between the y component of h, i.e., $h_{y01(2)}$ and $\boldsymbol{M}$. $w_{1(2)}$ is the width of the respective inner conductor. The voltage V_2 depends linearly on χ_{tot} which reflects the metamaterial properties. We show that micro- and nanopatterned antennas allow us to address, both, artificial band gap materials (where the wave length is in the order of the size of the building block) as well as metamaterials (where the periodicity is much smaller than the wavelength) [5].

2. Experimental Setup and Broadband Spectroscopy

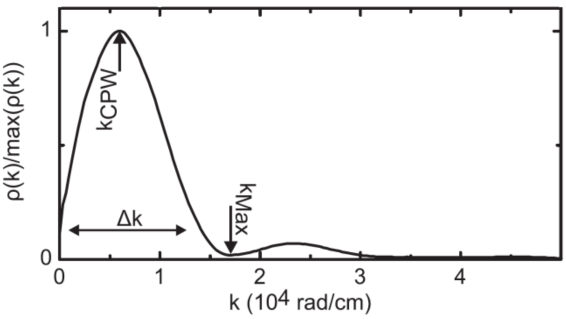
A broadband microwave probe station is employed to measure the induced voltages in the GHz regime [Fig. 1(a)]. A vector network analyzer (VNA) has two ports where it creates a sinusoidal microwave as an output signal and also detects the returning e-m waves. The typical microwave rf output power is 1 mW. Microwave probe tips are used to contact the waveguides. The tips are attached to the VNA

ISBN 978-952-67611-0-7

through impedance matched microwave cables. A static magnetic field H with values up to 100 mT is generated by two pairs of current coils and two pole shoes [6]. 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. All CPWs shown here 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) films or stripes. The permalloy is deposited on a gallium arsenide substrate using lift-off processing and covered by a silicon oxide layer.



(a)



(b)

Fig. 1: (a) Sketch of the probe station with VNA and field coils. (b) Normalized Fourier transformation of the current density distribution of a coplanar waveguide having an inner conductor width of 2 µm.

Key to address magnonic metamaterials is the excitation of spin waves of different wave vectors k_{CPW} and wave vector distributions Δk [cf. Fig. 1(b)]. In our experiments we employ different CPW designs in order to excite different k. In Fig. 2(a) we show a CPW having an inner conductor width of $w_i = 20$ µm. One can readily estimate k_{CPW} according to [7] $k_{CPW} = \frac{\pi}{w_i + 2w_g}$, where w_g is the distance between signal and ground lines. For the CPW of Fig. 2(a) we get $k_{CPW} = 0.07 \times 10^4$ rad/cm. To be more precise a CPW provides a considerable excitation strength $\rho(k)$ distributed over a range Δk of k values. $\rho(k)$ is extracted from the Fourier transformation of the CPW's current distribution. In Fig. 1(b) the relevant parameters are defined. Here, we have assumed $w_i = 2$ µm giving rise to $k_{CPW} \sim 0.6 \times 10^4$ rad/cm. To explore spin wave propagation in magnonic devices we prepare microwave antennas consisting of two CPW's in parallel. In such a case the first (second) CPW is used to excite (detect) the spin waves, i.e., we have an emitter and detector configuration [Figs. 2(c) and (e)]. In experiments on permalloy antidot lattices [1] we have found that a separation D of 12 µm provides a good compromise between a strong SW signal at the detector and substantially suppressed direct e-m crosstalk between the two waveguides. In Fig. 2(c), $k_{CPW} = 0.5 \times 10^4$ rad/cm. Figure 2(e) shows a CPW where we follow the approach of Bailleul et al. [8]. This meander-type design allows us to obtain compact CPWs providing a narrow distribution Δk. In this case $\rho(k)$ has a dominant contribution at a wave vector given by [8] $k_{CPW} = \frac{2}{w_i + 2l_1 + 3l_p + 2l_2}$, where l_1 is the distance between inner and outer lines, l_p is the width of the outer line and l_2 is the intermediate distance of the meander.

Spectroscopy data are presented in Fig. 2 (b), (d) and (f) taken with the three different CPWs as displayed. Note that from left to right the most prominent resonances gain considerably in frequency. This reflects the increased k. The different intensities are a result of different $\rho(k)$. Even the small inner conductor of $w_i = 320$nm in Fig. 2(e) provides us with a very good signal-to-noise ratio. This allows us to investigate the dynamic response at large k values even beyond 3.4×10^4 rad/cm as indicated by the weak but well resolved high frequency mode in Fig. 2(f). Thereby our antenna generates *k* values as large as the ones used in inelastic light scattering experiments. This turns out to be key to explore magnonic metamaterials in detail [1].

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant No. 228673 Magnonics and the German excellence cluster 'Nanosystems Initiative Munich'.

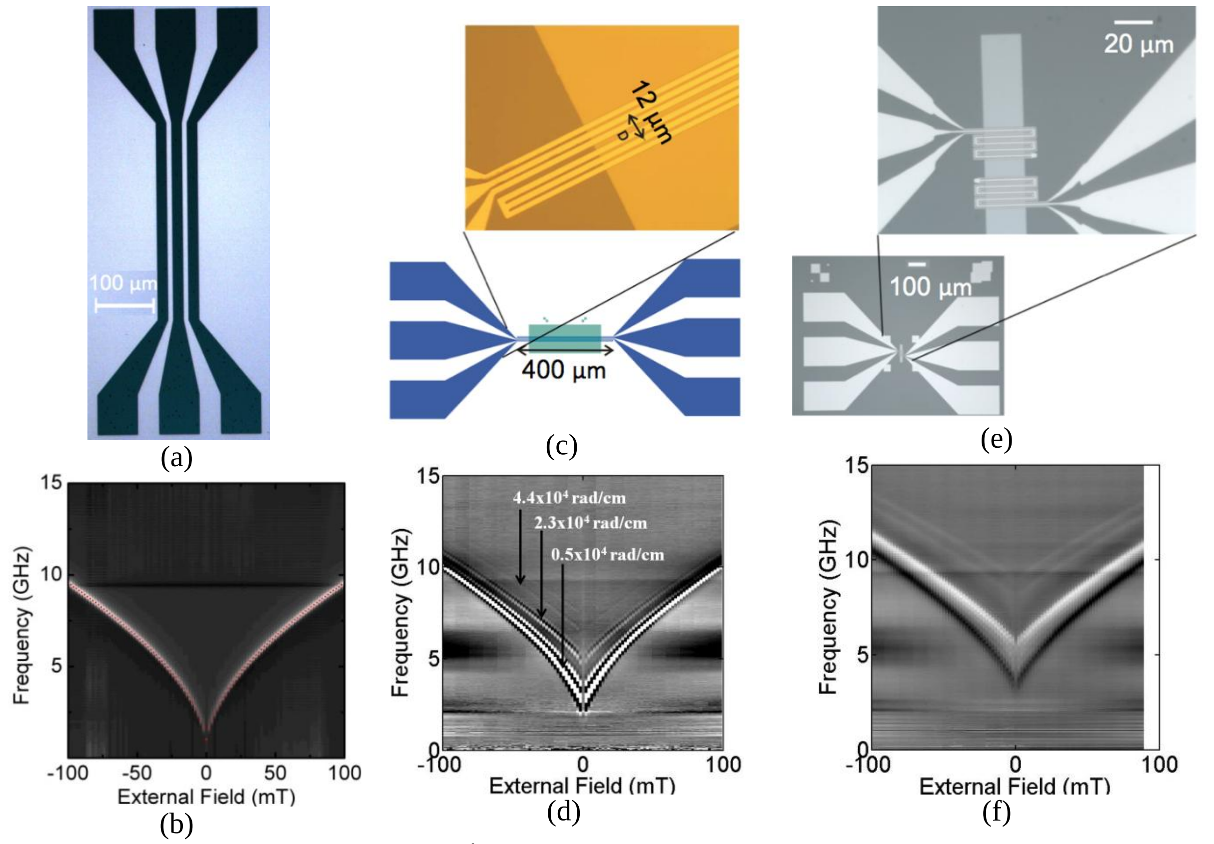


Fig. 2: (a) CPW with $\boldsymbol{k_{CPW} = 0.07 \times 10^4}$ **rad/cm** (black indicates metal lines) used for (b) field-dependent broadband spectroscopy on a ferromagnetic film. The bright curve follows the expected ferromagnetic resonance. (c) Emitter and detector antennas (in the optical micrograph bright yellow color indicates metal lines) used for (d) propagating spin wave spectroscopy reflecting $\boldsymbol{k_{CPW} = 0.5 \times 10^4}$ **rad/cm** as the most prominent resonance. Further relevant *k* are listed. The oscillating black-white contrasts originate from SW phase shifts [1]. (e) Meander-type design following Ref. [8] (in the scanning electron microscopy images bright gray indicates metal lines) supporting $\boldsymbol{k_{CPW} = 3.4 \times 10^4}$ **rad/cm** mainly and (f) corresponding spectroscopy data taken on a ferromagnetic stripe. $Ni_{80}Fe_{20}$ is always about 25 nm thick.

References

[1] S. Neusser, G. Duerr, H. G. Bauer, S. Tacchi, M. Madami, G. Woltersdorf, G. Gubbiotti, C. H. Back, and D. Grundler. *Phys. Rev. Lett.*, Vol. 105, p. 067208, 2010.

[2] G. Gubbiotti, S. Tacchi, M. Madami, G. Carlotti, A. O. Adeyeye, and M. Kostylev. *J. Phys. D: Appl. Phys.*, Vol. 43, p. 264003, 2010.

[3] J. Topp, D. Heitmann, M.P. Kostylev, and D. Grundler. *Phys. Rev. Lett.*, Vol. 104, p. 207205, 2010.

[4] O. Kasyutich, A. Sarua, and W. Schwarzacher. *J. Phys. D: Appl. Phys.*, Vol. 41, p. 134002, 2008.

[5] S. Neusser, Ph D thesis, Technische Universität München, in preparation.

[6] F. Giesen, J. Podbielski, T. Korn, and D. Grundler, *J. Appl. Phys.*, Vol. 97, p. 10A712, 2005.

[7] K. J. Kennewell, M. Kostylev, and R. L. Stamps. *J. Appl. Phys.*, Vol. 101, 09D107 (2007).

[8] V. Vlaminck and M. Bailleul. *Phys. Rev. B*, Vol. 81, p. 014425, 2010.

