Perfect imaging with spin-waves

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Abstract

We show that a spin-wave system can be used for perfect imaging by utilizing the anisotropic dispersion relation for spin waves. Such a system can be seen as a spin-wave hyperlense in analogy to perfect imaging concepts from metamaterial research in optics. The resolution of the spin-wave images is only limited by the damping of the spin-waves and by the finite curvature of the isofrequency curve in k-space.

1. Introduction

The possibility to control the propagation of electromagnetic waves by tailoring the optical parameters of a metamaterial promises a wide range of new fundamental concepts and applications. Hyperlenses allow the imaging of subwavelength objects by providing a strongly anisotropic medium for the propagation of light waves [1, 2] to overcome the diffraction limit [3]. In analogy to this, we show here a magnonic hyperlense for spin waves: The strong anisotropy of spin-wave propagation in a ferromagnetic film can be employed for the perfect imaging of a one-dimensional grating.

2. Perfect Imaging of a Grating

We use a time-resolved scanning Kerr microscope (TR-SKM) to examine spin waves in a Permalloy (Py) sample with a spatial resolution of 300 nm and a temporal resolution of a few picoseconds (for details of the setup see [5]): The experimental setup is sketched in Fig. 1. By passing a microwave through a coplanar waveguide (CPW), spin waves are excited in the Py sample. The CPW, consisting of ground lines G1 and G2 and a signal line S, is deposited on top of a GaAs substrate. The Py sample is a 22 nm thick film with a rectangular shape (length l = 280 µm in x direction and l = 120 µm in y direction). It exhibits a grating with a period p = 4 µm, realized by 13 square shaped holes in the film, at a distance of 10.5 µm from the signal line. The magnetization of the Py sample is probed via the magneto-optical Kerr effect with a focused femtosecond laser (800 nm, 150 fs pulse width, 76 MHz repetition rate), which triggers the exciting microwave and allows for snap shots of the wave field at a desired phase, i.e. a fixed point in time. Figure 1 shows such a TR-SKM image of the spin-wave field, overlaid on top of the sample sketch to illustrate the spin-wave propagation in the system. A plane spin wave is excited at the signal line and propagates towards the grating. At the grating the spin wave is partly transmitted and partly reflected. The transmitted part forms distinct spin-wave patterns. These spin-wave patterns generate images of the spin-wave distribution inside the slits, as we will discuss in the following.

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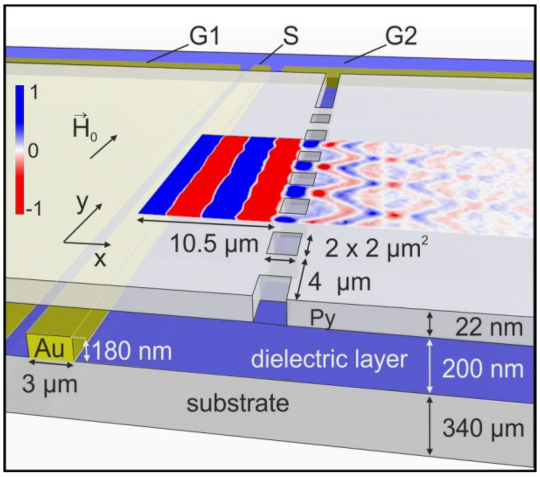

Fig. 1: Sketch of the experimental arrangement. Spin waves are excited in a Py film with microwave passing through a coplanar waveguide, which consists of the ground lines G1 and G2 and a signal line S. The spin wave field (overlaid as a color plot) is imaged with time resolved scanning Kerr microscopy. A grating is realized by micrometer sized square shaped holes in the Py film.

Figure 2 (a) shows TR-SKM images of the spin wave behind the grating for a spin-wave frequency $f = 4028$ MHz, with an externally applied magnetic field of μ_0H = 20 mT. The grating is marked by the black hollow squares. A distinct interference pattern is generated, which is periodic in *x* direction and in *y* direction. We find distinct maxima in the Fourier transformation of this spin-wave pattern, as shown in Fig. 2 (b). The positions of these maxima in *y* direction (k_{BV}) correspond to the periodicity *p* of the grating. The related *x* components (k_{DE}) are imposed by the anisotropic dispersion relation for spin waves. An analytical calculation of isofrequency curves following Kalinikos et al. [4] is shown by the red dashed lines. We can fit the positions of the maxima very well by assuming a saturation magnetization of 940 mT.

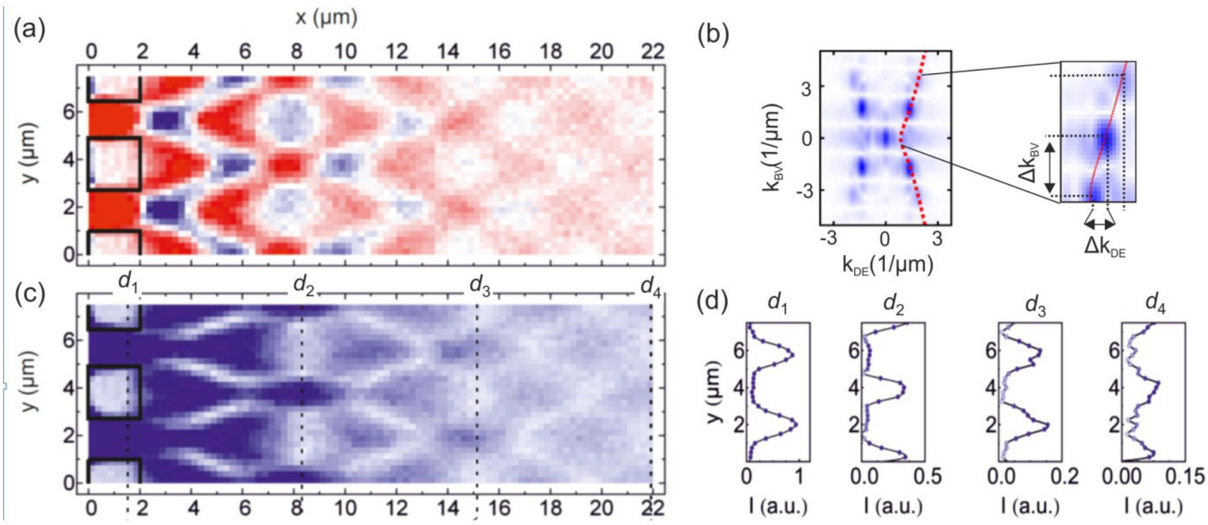

Fig. 2: (a) TR-SKM image of the spin-wave behind the grating for $f = 4028$ MHz and $\mu_0H = 20$ mT. (b) Fourier spectrum of the spin-wave pattern shown in (a). (c) Intensity distribution of the spin-wave pattern shown in (a). (d) Cross sections of the spin-wave intensity at the dotted lines in (c).

Figure 2 (c) shows the measured intensity distribution corresponding to the TR-SKM image shown in Fig. 2 (a). To obtain such a plot, we scan through a complete period of the spin dynamic and take the

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maximum deflection for each point of the measured area. Fig. 2 (d) shows cross sections along the *y* direction of this intensity distribution at the position of the grating and at the positions of the image lines d_1 = 1.50 µm, d_2 = 8.25 µm, d_3 = 15.00 µm and d_4 = 21.75 µm. The intensity distribution at the grating is replicated at equidistant positions $\Delta d/2$ behind the grating. Every second replication is shifted by half the grating period. In fact, these replications represent perfect two-dimensional spin wave images of the spin-wave distribution inside the slits of the grating as we will discuss in the following.

In general, to obtain a perfect image all Fourier components present at the object have to reach the respective image line (condition I), and they have to be superimposed with the right phase and with the right relative amplitudes (condition II). Condition I is fulfilled, because the isofrequency line in *k* space (red line in Fig. 2 (b)) crosses all Fourier components which exhibit a considerable intensity, so that all necessary components are allowed to propagate into the film. Condition II is fulfilled due to the fixed linear relation between Δk_{DE} and Δk_{BV}, i.e. $\Delta k_{DE} = \varkappa\ \Delta k_{BV}$, which is imposed by the linear slope $\varkappa$ of the dispersion as illustrated by the zoom-in in Fig. 2(b). This leads to a beating pattern in real space which exhibits image lines at periodic distances $\Delta d = 2\pi/\ \Delta k_{DE} = p/\ \varkappa$, at which the phases of all Fourier components correspond to the grating cross section. Furthermore, halfway between these image lines, additional image lines exist, where the phases of all Fourier components are shifted by 180° compared to the grating cross section, leading to an image shift in the *y* direction by $p/2$.

3. Conclusion

In conclusion, we show perfect imaging with spin waves utilizing their anisotropic dispersion. The quality of these images is only limited by the deviations of the isofrequency curves in *k* space from a linear shape and by the damping of the spin waves. This system enables the imaging of objects by spin waves with dimensions far below the wavelength of the incident spin wave and can be understood in full analogy to directed sub wavelength imaging as theoretically discussed by Wood et al in Ref. [5] for anisotropic optical metamaterials. Since in the case of spin waves the dispersion shape can be tailored in situ by the external magnetic field and the frequency, spin waves in ferromagnetic films provide a unique model system for the study of wave propagation in such anisotropic media. Apart from this, our spin wave imaging concept opens up new pathways for the controlled spin-wave confinement in unpatterned films, e.g., to realize novel logic devices.

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