

All-electrical detection of spin dynamics in magnetic antidot lattices by the inverse spin Hall effect

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The understanding of spin dynamics in laterally confined structures on sub-micron length scales has become a significant aspect of the development of novel magnetic storage technologies. Numerous ferromagnetic resonance measurements, optical characterization by Kerr microscopy and Brillouin light scattering spectroscopy and x-ray studies were carried out to detect the dynamics in patterned magnetic antidot lattices. Here, we investigate Oersted-field driven spin dynamics in rectangular $\text{Ni}_{80}\text{Fe}_{20}/\text{Pt}$ antidot lattices with different lattice parameters by electrical means and compare them to micromagnetic simulations. When the system is driven to resonance, a dc voltage across the length of the sample is detected that changes its sign upon field reversal, which is in agreement with a rectification mechanism based on the inverse spin Hall effect. Furthermore, we show that the voltage output scales linearly with the applied microwave drive in the investigated range of powers. Our findings have direct implications on the development of engineered magnonics applications and devices.

Magnonic crystals, a new class of metamaterials with periodically modulated magnetic properties, have emerged as key building blocks in magnonics¹. The realization of spin-wave filters², phase shifters³, interferometers⁴, spin-wave logic devices⁵ and grating couplers⁶ has been demonstrated and it is possible to tune the magnonic properties as desired by engineering the magnetic properties of the magnonic crystal. In this regard, ferromagnetic antidot lattices are prototypes of magnonic crystals. The periodicity, dimensions, shape and material of an antidot lattice dictate the spin-wave frequencies and their spatial distribution. These characteristics are influenced by inhomogeneities of internal magnetic fields in lattices with larger periods, whereas at smaller periods exchange fields play an important role⁷. Since those parameters can easily be tuned by designing the pattern and choosing the proper material, antidot lattices are of fundamental importance in magnonics.

Spin dynamics in antidot lattices were investigated by numerous resonance measurements^{8–10}, by x-ray spectroscopy¹¹ and by optical techniques such as Kerr microscopy and Brillouin light scattering spectroscopy^{8,9,12,13}. In order to utilize antidot lattices in real magnonic applications, however, it is desirable to integrate them in conventional dc electronic devices and circuitries. The optimal signal processing pathway is¹⁴: input electronic charge signal \rightarrow spin current signal \rightarrow magnonic signal \rightarrow spin current signal \rightarrow output electronic charge signal, see Fig. 1(a). Signal processing and transfer can be realized by magnons and ultimately it would be possible to harness the unique and controllable

magnon characteristics of the antidot lattice for real applications.

On one hand, spin Hall effects^{16,17} have been proven to be excellent candidates for the interconversion between electronic charge and spin currents¹⁵, and on the other hand, spin pumping^{18–22} and spin-transfer torque^{23,24} effects are important methods to transform magnonic signals to spin currents and vice versa^{25–28}. We will focus here on the detection side of the conversion pathway: the transformation of a magnonic signal (spin dynamics) into

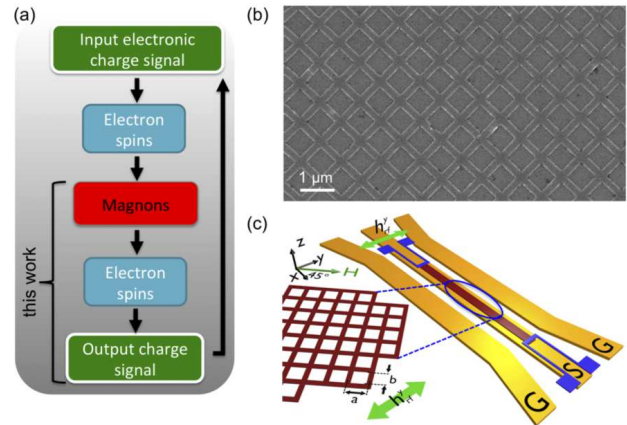


FIG. 1. (Color online) (a) Pathway for signal processing from an electronic to a magnonic signal and back. Signal processing can be achieved by magnons. (b) Example of a scanning electron microscopy image; here: antidot lattice B with $a = 845$ nm and $b = 585$ nm. (c) Schematic of the experimental setup. The antidot lattice is oriented at 45° with respect to the signal line S . The dimensions a and b are given in Tab. I.

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TABLE I. Overview of the investigated antidot lattices. Py thickness: 15 nm, Pt thickness: 5 nm.

Antidot lattice	lattice constant a (nm)	hole width b (nm)
A	755	519
B	845	585
C	942	713

an electronic dc charge signal, see Fig. 1(a).

In this Letter, we investigate spin dynamics in rectangular antidot lattices made of bilayers consisting of a ferromagnetic $\text{Ni}_{80}\text{Fe}_{20}$ layer (permalloy, Py) and a Pt capping layer with varying dimensions and periodicity. In contrast to conventional resonance experiments, where dynamics is driven by a microwave signal and the response of the magnetic systems is quantified by an absorption method, we use a rectification mechanism based on pure dc techniques. Spin dynamics in the Py layer are induced by a microwave driven Oersted field and detected by dc voltage that is explained by a rectification based on the inverse spin Hall effect (ISHE) in the Pt. It is shown that various modes determined by the design of the pattern contribute to the dc voltage proving the possibility to utilize engineered antidot lattices for information processing/transport integrated in dc circuitries. The mode spectrum is confirmed by micromagnetic simulations. Power dependent measurements confirm a linear response of the antidot lattice, which is desirable for the development of electronic devices.

The samples were fabricated in the following fashion: In a first step, dc leads were fabricated by magnetron sputtering and photolithography on intrinsic Si substrates with a 300 nm thick thermally grown SiO_2 layer. The antidot lattices of various dimensions were then written by electron beam lithography (see Tab. I). A double layer positive resist of PMMA was spin-coated prior to electron beam exposure. After exposure and development, 15 nm-thick permalloy and 5 nm-thick Pt layers were deposited using electron beam evaporation at rates of $<0.3 \text{ \AA/s}$ without breaking the vacuum. The resist was lifted-off in acetone. Figure 1(b) shows a typical scanning electron microscopy image (SEM), for lattice B, see Tab. I. The antidot lattices cover an area of approximately $800 \times 20 \mu\text{m}^2$ in total and the lateral dimensions of each investigated antidot lattice is summarized in Tab. I. In a subsequent step a 50Ω -matched coplanar waveguide (CPW) made of Ti/Au (3 nm/150 nm) was fabricated by magnetron sputtering and photolithography. The antidot lattice and the CPW were separated by a 80 nm-thick MgO layer to avoid any electrical contact and the dc leads are kept between the central line and the ground plate within the CPW in order to minimize inductively coupled currents in the sample.

Figure 1(c) illustrates the experimental setup and the measurement configuration. The microwave driven Oersted field (in y -direction) is aligned at 45° to the external magnetic field [in (1, 1)-direction; CPW and external

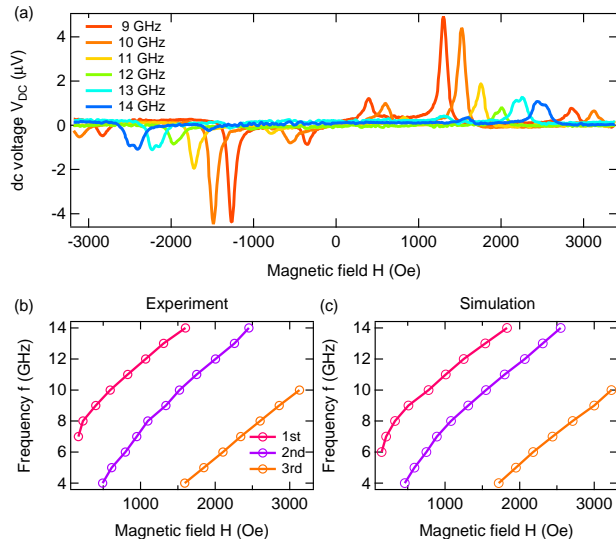


FIG. 2. (Color online) (a) Typical dc voltage spectrum (here: antidot lattice B) measured at an applied power of +15 dBm. The low frequency spectra are omitted to provide better readability. The resonance signals show a mostly symmetric Lorentzian lineshape and change their polarity upon field reversal. (b) Frequency vs. field relation extracted from the spectrum shown in Fig. 2(a) for the three modes that can be identified clearly. (c) Simulated frequency vs. field relation, here: antidot lattice B.

field are oriented at an angle of 45°], whereas the square antidot lattice is oriented parallel to it. Magnetization dynamics is excited by the Oersted field generated by a microwave current in the CPW. We use an amplitude modulation of the signal generator and lock-in technique to detect the dc voltage output. For a particular measurement, the rf power and frequency are kept constant (power range +10 to +18 dBm, frequency range: 4 to 14 GHz) while the external magnetic field is swept and the dc output is recorded. When the system is driven to resonance, the magnetization precession in the Py layer generates a spin accumulation at the Py/Pt interface that diffuses into the Pt layer, a phenomenon that is known as spin pumping effect¹⁸. This spin current gives rise to an electronic charge imbalance in the Pt layer due to the inverse spin Hall effect. The conversion from a spin- into charge current is described by:

$$\vec{J}_C \propto \theta_{\text{SH}} \vec{J}_S \times \vec{\sigma}, \quad (1)$$

where \vec{J}_C is the charge-current density, θ_{SH} the spin Hall angle that describes the efficiency of the conversion, \vec{J}_S is the spin-current density and $\vec{\sigma}$ is the spin polarization vector.

The investigation of different mode spectra in antidot lattices and the examination of the underlying effects is very intriguing and subject of many studies in magnonics. However, we focus here on the fact that these well known resonances can indeed be detected by pure dc electrical means. A typical bi-polar spectrum recorded at an

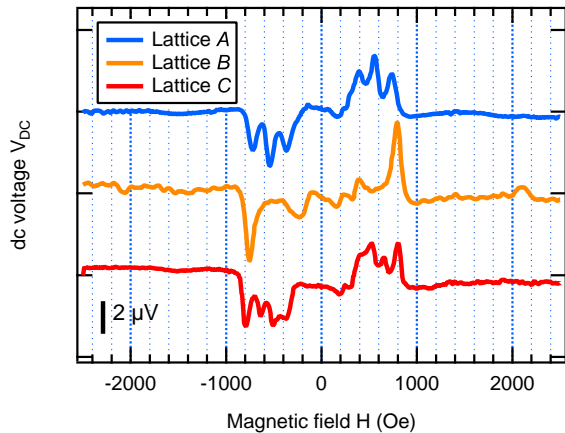


FIG. 3. (Color online) Comparison of the voltage spectra of the different antidot lattices at a fixed excitation frequency of 6 GHz and microwave power of +15 dBm. The lattices feature the following stadium widths ($a - b$) and whole width b . A: ($a - b$) = 236 nm, b = 519 nm, B: ($a - b$) = 260 nm, b = 585 nm, C: ($a - b$) = 229 nm, b = 713 nm.

applied power of +15 dBm is shown in Fig. 2(a) (here shown: antidot lattice B). We clearly observe distinct modes in the dc spectra at particular frequency–field values. The low-frequency modes are not shown in Fig. 2(a) to increase the readability of the viewgraph. As is apparent from the figure, the modes exhibit a mostly symmetric Lorentzian lineshape. The most likely source for this behavior is a spin-to-charge current conversion due to the ISHE. For an unstructured sample oriented in the same way as here or if there was a substantial phase shift between the rf current and the magnetization oscillation present, we would expect to observe a larger antisymmetric contribution if the signal was dominantly generated by a rectification due to the anisotropic magnetoresistance (AMR)²⁹. Besides that, the polarity of the voltage signal changes sign when the magnetization direction is changed [Fig. 2(a)], which also suggests that the observed voltage is most likely due to the ISHE²⁹, Eq. (1). However, other effects such as spin rectification²⁹, magnonic charge pumping^{30,31} or AMR²⁹ cannot be completely ruled out. Independent of the rectification mechanism the experimental data unambiguously demonstrates an easy way to detect spin dynamics in magnonic crystals by pure dc electrical means. Furthermore, it is interesting to note that the magnitude of the detected dc signal is comparable to that of unpatterned Py/Pt stripes³². In the spectrum shown in Fig. 2(a) we can clearly distinguish three different modes. We analyze their frequency–magnetic field dependence as shown in Fig. 2(b). As expected from the Kittel equation, the resonance frequency increases with the externally applied magnetic field. In order to corroborate the experimentally observed spectra, micro-magnetic simulations were performed using mumax3^{33,34}. An exceptional good agreement between the theoretically

expected and experimentally observed spectra is found. As in experiment three modes are found in the investigated magnetic field range, see Fig. 2(c).

Figure 3 compares the dc voltage spectrum of the investigated antidot lattices, excited at 6 GHz and +15 dBm. The different lattices show distinct features in the mode structure. The modes of lattice A and C lie closer together than those of B, leading to the conclusion that dipolar interactions emerging for narrower stadium widths ($a - b$) are the dominant tuning parameter here (see Tab. I). On the other hand, for the larger width b , a larger resonance field is observed. This can be understood as a decrease of demagnetization with increasing b and, thus, an increase of the resonance field at a particular excitation frequency¹⁰. The magnitude of the detected voltage is basically independent of the lattice parameters, see Fig. 3. This demonstrates the possibility to tune the magnonic frequency characteristics as desired.

Next, we will focus on power-dependent studies. Linear response is a necessary requirement for the utilization of potential magnonic devices in electrical circuits. Therefore, we carried out microwave power dependent measurements. As is apparent from the power dependence shown in Fig. 4 that the dc signals of all three modes increase with power. The magnitude of the output signal of each mode as a function of power is shown in the inset in Fig. 4 (please note the linear scale; P in mW). We can draw two important conclusions from this measurement. Firstly, we observe a linear response of the system: the output signal increases linearly with the drive in the investigated range of applied powers. This shows that we operate in the linear regime and no nonlinear dynamics is excited. Secondly, the first and third mode show approx-

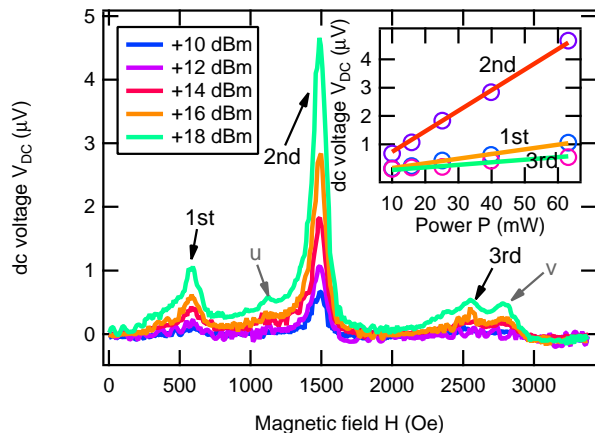


FIG. 4. (Color online) Voltage spectrum as function of the applied microwave power at an fixed excitation frequency of 10 GHz (antidot lattice A). Three modes denoted as 1st, 2nd and 3rd, are detectable at all microwave powers. At higher powers additional modes (labeled as u and v) emerge. The inset illustrates the linearity of the generated dc output voltage with power; please note the linear scale of the power.

imately the same power dependence, whereas the second mode increases much faster with power. This might particularly be of interest for the development of magnonic devices where frequency/field dependent threshold output signals can be addressed by choosing an appropriate excitation power. Moreover, additional modes, which are not detectable at low powers emerge at higher excitation powers, e.g., at 1100 Oe and 2800 Oe for $f = 10$ GHz (labeled as u and v in Fig. 4). Since we observe a linear behavior of the three initial modes without any saturation, the modes u and v are not associated with the onset of nonlinear effects. The reason why they can only be detected at higher microwave powers is a better coupling of the driving fields to the magnetization.

In summary, we investigated the detection of spin dynamics in different square antidot lattices made of ferromagnetic metal - normal metal (Py/Pt) bilayers by means of spin pumping and inverse spin Hall effect. These investigations reveal that different modes characteristic for antidot lattices can be observed by *dc* voltage output signals. Furthermore, we showed that the voltage signals of all modes scales linearly with the applied microwave power, yet the strongest mode shows the largest signal increase with power, which might directly affect the development of magnonic devices. Our studies demonstrate an easy way to investigate the properties of antidot lattices by a simple detection scheme and, even more importantly, the feasibility of an integration of antidot lattices as processing and transport devices in conventional electronics. However, in order to realize a full circle of conversion from an electronic to a magnonic signal and back to an electronic signal [Fig. 1(a)], the first conversion process by spin Hall and spin-transfer torque effect remains to be explored. Furthermore, our work suggests that a local detection and excitation of spin dynamics might be possible by covering only selective areas of the antidot lattice with Pt.

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