

Brillouin scattering of light by spin waves in ferromagnetic nanorods

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ABSTRACT

We report the investigations of spin wave modes of arrays of Ni and Co nanorods using Brillouin light scattering. We have revealed the significant influence of spin wave modes along the nanorod axis in contrast to infinite magnetic nanowires. Unusual optical properties featuring an inverted Stokes/anti-Stokes asymmetry of the Brillouin scattering spectra have been observed. The spectrum of spin wave modes in the nanorod array has been calculated and compared with the experiment. Experimental observations are explained in terms of a combined numerical–analytical approach taking into account both the low aspect ratio of individual magnetic nanorods and dipolar magnetic coupling between the nanorods in the array. The optical studies of spin-wave modes in nanorod metamaterials with low aspect ratio nanorods have revealed new magnetic and magneto-optical properties compared to continuous magnetic films or infinite magnetic nanowires. Such magnetic artificial materials are important class of active metamaterials needed for prospective data storage and signal processing applications.

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1. Introduction

Potential applications to the microwave frequency devices motivate interest in high-frequency dynamics of arrays of magnetic nanorods [1]. In the case of relatively low angle precession, magnetic dynamics manifests itself through bulk magnetic excitations known as spin wave (SW) modes [2]. One of the attractive features of such structures, owing to their geometry, is the possibility to synthesize materials with a desirable value of uniaxial magnetic anisotropy oriented along the rod axis. Breakthroughs in the technology of electrodeposition of ferromagnetic metals (Co, Ni, permalloy) in arrays of self-assembled cylindrical nano-pores created in alumina Al_2O_3 films have accelerated the development of this concept.

Previous experimental efforts relied mainly on the Ferromagnetic Resonance (FMR) measurements in its wide-band strip-line/VNA (Vector Network Analyser) version [3–6]. The influence of inter-rod dipole interactions was investigated on dynamic properties of Ni nanowire arrays in a wide range of packing densities P (4% to 38%) and the wire diameters (56 to 250 nm) [3–5]. The dipolar interactions between the wires were modeled, according to a mean-field approach assuming an effective uniaxial

anisotropy field oriented perpendicular to the wire axis and proportional to the membrane porosity.

Similarly, interesting effects in CoFeB ferromagnetic nanowire arrays, associated with two magnetization populations, one for nanowires with upward magnetization and one with downward magnetization have been addressed in Ref. 4. It should be noted that until now all experimental studies have been performed on wires nanometric only in cross-section, their length typically being of the order of tens of microns (aspect ratio R typically over 100).

Brillouin light scattering (BLS), based on magneto-optical (MO) interaction of light with SW modes localized on nanowires, is an alternative technique to probe magnetic excitations in nanowires [7]. In contrast to earlier experimental results obtained on wires of practically infinite height (high aspect ratio $R > 100$), the role of “vertical” SW resonances, along the axis of the nanorod of low aspect ratios ($R < 10$), turned out to be very important as well as that of the near-field nature of MO interactions in such nanorod arrays.

In this paper, we address the mechanisms of Brillouin scattering of light by spin waves in ferromagnetic nanorods made of ferromagnetic metals, such as nickel and cobalt, of finite aspect ratio, ranging from 2.5 to 9.

To simulate magnetic properties of the array of Ni and Co nanorods, the geometry used in the experiment, semi-analytical was used in order to avoid unrealistically long computation time.

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First, we numerically analyzed the SW modes existing in an isolated cylindrical nanorod, applying either an ad hoc home made code based on the finite element (FE) method and making use of the Fluctuation-Dissipation Theorem or the standard OOMMF (Object Oriented Micro Magnetic Framework) based on the finite difference (FD) technique. Both approaches are equally applicable, each having its advantages and disadvantages.

To take into account the dipolar interactions between nanorods, we made use of the approach based on the effective field of magnetic anisotropy, proposed in Ref. [5]. In this paper, the shape magnetic anisotropy is regarded as a result of a competition of the anisotropy of a single rod, which is equal to $2\pi M_s$ for an infinite cylinder, and that of a quasi-continuous planar film engendered though inter-wire magnetic dipolar interactions. The authors of this work have supposed that the latter contribution is simply proportional to the packing density P , also known as filling factor, being expressed in the following way $-6\pi M_s P$. Since in our case the cylinders are finite we extracted the true value of the anisotropy of an individual rod from numerical simulations.

In this paper, we focus equally on optical mechanisms underlying magneto-optical (MO) Brillouin light scattering by magnons with the frequencies in the 3–30 GHz range. Special attention will be paid to the mechanisms of the MO near-field interactions in metal nanoparticles of cylindrical shape. The above mentioned effects are crucial for explaining the unusual optical properties featuring an inverted Stokes/anti-Stokes asymmetry of the Brillouin scattering spectra that have been observed. Thus magnetic nanorod arrays are an important class of metamaterials, both optically and magnetically, that may have significant influence on magnetic and magneto-optical data storage as well as important for the development of active plasmonic metamaterials for optical signal control.

Ni and Co nanorod arrays were electrodeposited in the anodized aluminium oxide (AAO) templates. Template fabrication involved RF magnetron sputtering of a thin film multilayer comprising of Al on top of gold and tantalum buffer layers. One can find more detailed description in Ref. [8,9].

The experimental studies of spin-waves in magnetic nanorods consisted of two series of measurements carried out on three representative samples, whose geometry is illustrated in Fig. 1 and Table 1.

All the samples have the same height and approximately the same filling factor P , while the diameter and, consequently, the aspect ratio R vary considerably, for too different ferromagnetic metals (nickel and cobalt). The arrays in the samples are not perfectly ordered, as one can see in Fig. 2.

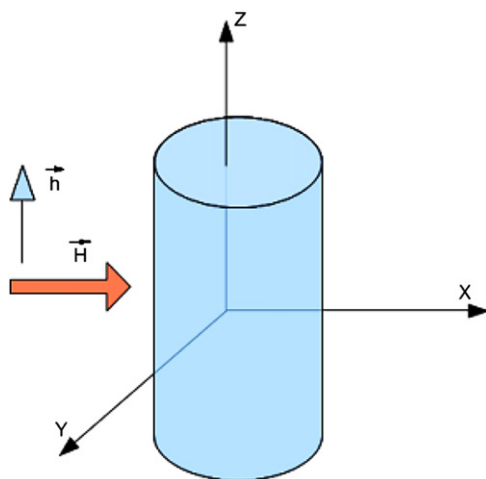


Fig. 1. Geometry of a ferromagnetic nano-rod.

Table 1

Sample	1	2	3
Material	Ni	Ni	Co
Rod diameter (nm)	70	20	30
Rod height (nm)	175	175	175
Aspect ratio R	2.5	9.0	6.0
Filling factor P (%)	15.5	12.5	15.0

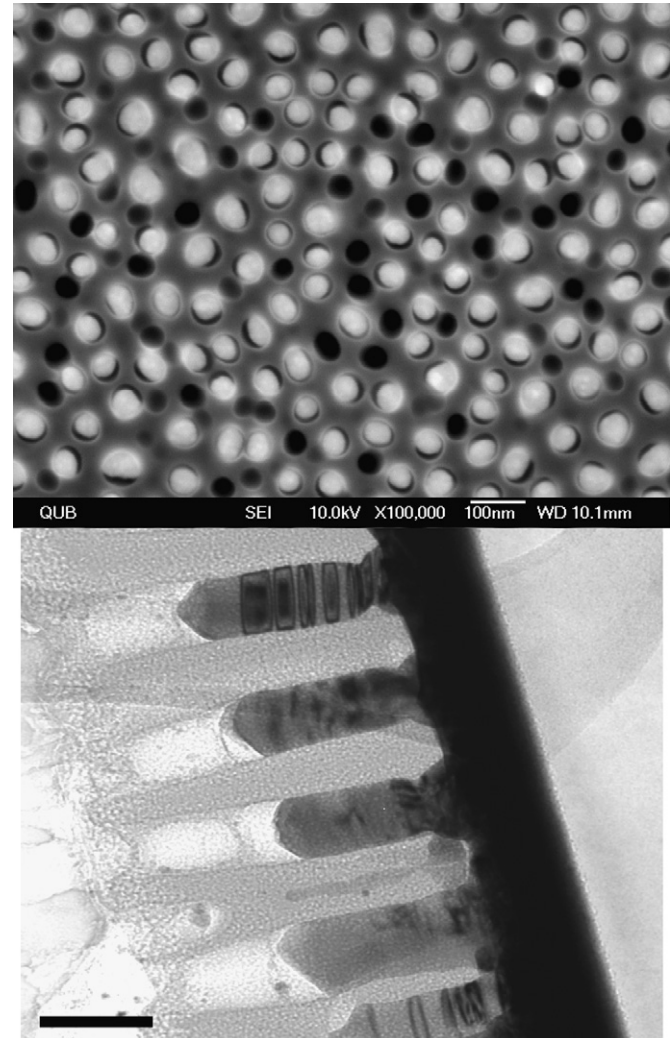


Fig. 2. (Upper panel) SEM image of Ni nanorods grown in 70 nm pores (sample 1), the Aluminum oxide has been briefly etched to expose the rods. (Lower panel) TEM cross-section of 70 nm Ni rods (sample 1).

First, the BLS spectra were measured at the fixed angle of incidence ($\theta=45^\circ$) for varying applied magnetic field from -13 kOe to $+13$ kOe with a step 1 kOe. In the second experiment, the dispersion of modes was measured at a fixed magnetic field by varying the angle of incidence.

Three typical BLS spectra, each representing one of the three samples, and belonging to the first series, are given in Fig. 3: (a) Sample 1, $H=7000$ Oe (b) Sample 2, $H=5000$ Oe, while Fig. 4 represents the results obtained on Sample 3, $H=11,000$ Oe, for the same angle of incidence $\theta=45^\circ$. The spectra consist of the central elastic scattering (Rayleigh) peak surrounded by the two dominating Stokes and anti-Stokes Brillouin scatterings.

The major features appearing in these figures can be summarized as follows. First, they all demonstrate a pronounced S/AS

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