Magnetic normal modes of elliptical NiFe nanoring studied by micro-focused Brillouin light scattering

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Abstract. Micro-focused Brillouin light scattering (µ-BLS) technique is employed to study the magnetization dynamics of a single elliptical NiFe nanoring. Spin waves spectra, recorded at different positions within the ring, compare very well to the results of dynamical micromagnetic simulations, confirming the exact spatial symmetry and localization region of each of the detected modes. In addition, a comparison with the spectra acquired by conventional Brillouin light scattering on a large array of identical nanorings enables us to show the superiority of µ-BLS for the study of stationary and localised modes within nanomagnets.

1. Introduction
In the last decade, there has been growing interest in the study of the dynamic properties of laterally confined nanostructures due to advances in nanofabrication and characterization techniques. Among the latter, one can consider ferromagnetic resonance (FMR), time-resolved magneto-optical Kerr effect (MOKE) and Brillouin light scattering from spin waves (BLS). While FMR cannot achieve lateral resolution to study magnetization dynamics of single nanomagnets, both TR-MOKE and BLS have done significant advances and have successfully achieved sub-micrometric lateral resolution, preserving a sizeable signal to noise ratio. [1,2,3] This means that they are true microscopy techniques, capable of spatially mapping spin excitations within a single nano-magnet.

In this paper, we present the results of a detailed investigation of both the frequencies and the spatial profiles of magnetic eigenmodes in a single elliptical Ni₈₁Fe₁₉ nanoring. These results are obtained using a micro-focused BLS apparatus (µ-BLS), recently setup at Perugia University [4]. It is important to recall that in a conventional BLS experiment the laser spot diameter is of about 30 μm, so that several thousands of nano-elements are usually illuminated, and the information obtained is averaged over such a large number of elements. For this reason, the attribution of a determined mode profile to the measured frequency can only be performed a-posteriori, in an indirect way, from a
comparison with simulated spectra. In addition, the localisation of modes in a narrow region of a magnetic element can result in a negligible cross section in a conventional BLS experiment.

2. Experimental

A schematic representation of the μ-BLS apparatus is shown in Fig. 1. It has been integrated into the already existing conventional BLS setup, based on a tandem Fabry-Perot interferometer for spin wave frequency shift detection (pink box). The new parts are the micro-focalization optical setup (green box) and the viewing setup for imaging the sample surface (blue box).

![Figure 1. Schematic representation of the μ-BLS setup](image)

The μ-BLS apparatus essentially consists of a XYZ piezo-scanning stage used as a sample holder and of a high magnification (100x) Mitutoyo Infinity-Corrected Long Working Distance Objective (PLAN APO) with numerical aperture (NA)=0.7 and working distance (WD)=6.0 mm. In order to image the micrometer-sized magnetic elements under investigation, a coaxial viewing system has been integrated into the micro-focused BLS setup. This system consists of a CCD camera supplied with a telescopic objective, two beam splitters and a source of white light (see Fig. 1). It uses the reflected light, separated from the scattered light by the polarizing beam splitter. The system allows the direct visualization of the sample surface and of the probing laser spot position during measurements. In order to reduce the laser intensity which reaches the CCD camera, an interference filter with a deep and narrow rejection band centred at 532 nm (Rugate Notch filter) is used. A quantitative estimation of both the lateral resolution (about 250 nm) and the axial resolution (about 1 μm)[5], were derived from reflectivity measurements on different sets of Al stripes deposited on Si, as discussed in Ref. [4].
3. Results

Ni81Fe19 elliptical rings, 20 nm thick, were fabricated by a combination of e-beam lithography, e-beam evaporation, and lift-off processes on a commercial oxidized Si wafer. The major axis of the ring is 1070 nm, the minor axis is 670 nm while the internal elliptic hole has a major axis of 380 nm and a minor axis of 120 nm. In Fig. 2, we present some spectra measured by μ-BLS in different positions, with an external magnetic field $H_{\text{ext}}=1.2 \text{kOe}$ applied along the major axis of the ring (so that its magnetization is in the onion state, as shown in the upper panel of Fig. 2). Position 0 corresponds to the laser spot focused at the centre of the longer arm of the ring and position 1 is shifted by 100 nm on the right side. Positions 2 and 3 correspond to the centre and to the outer border of the right ring arm, respectively. The μ-BLS spectra measured in the above positions are substantially different, as can be seen in Fig. 2. In particular, we notice that the spectrum at position 0, where the internal field is uniform and the magnetization is collinear with $H_{\text{ext}}$, presents several well resolved peaks. According to our micromagnetic simulations (Fig. 3) and to the nomenclature of the modes already introduced in the past [6,7] the mode exhibiting the largest BLS signal is the fundamental quasi-uniform mode (F) at 13.3 GHz (13.1 GHz in the simulation). It is characterized by the in-phase precession of all the spins and it exists in the rings arms parallel to the field direction.
where the internal field is almost uniform. At higher frequency (about 15.3 GHz in the experiment, 15.9 GHz in the simulation) there is a peak associated to a mode with one nodal plane parallel to the field direction (the so-called 1DE mode, having Damon-Eshbach character [6]). Below the F–mode frequency, instead, there is a peak at 11.5 GHz (11.9 GHz in the simulation) corresponding to a mode with two nodal planes perpendicular to the field (2BA, having a backward character [6]). As soon as the laser is moved to position 1, a sharp peak appears at about 12.6 GHz, associated to the 1BA mode (12.2 GHz in the simulation) which had a vanishing BLS cross section in position 0, because of its asymmetric character with respect to the short axis of the elliptical ring. At the same time both the F, the 2BA and the 1DE modes almost disappear, since their amplitude in position 1 is quite small as shown in Fig. 3. The overall shape of the spectrum changes dramatically when the laser spot is moved to the right arm of the ring, i.e. in position 2. A well pronounced peak appears in the experimental spectrum at about 10.4 GHz. According to micromagnetic calculations, it is associated to the so-called F-loc mode (calculated frequency 10.8 GHz), whose oscillation amplitude is very large in the middle of the left and right arms of the ring without nodal planes. Eventually, with the laser focused in position 3, the high frequency peaks have a reduced intensity while a well defined peak is present at 5.8 GHz. This is the end mode (EM-out) localised close to the outer border of the ring, which was not present at all in the spectra recorded in positions 0,1 and 2. Note that the calculated frequency of this mode is appreciably lower (4.7 GHz) than the experimental one, because the it is difficult to mimic the exact roughness and curvature at the ring edge. If we now compare the μ-BLS spectra measured in the above discussed positions with the conventional BLS measurement (top spectrum in Fig. 2) it appears that in the latter some modes are barely visible or completely missing. In particular, there is no trace of the EM-out, because its marked localization and its dependence on the morphology of each individual dot correspond to negligible cross section in standard measurements, which are averaged over thousands of rings.

In conclusion, we demonstrated the unique capability of μ–BLS in mapping-out the spatial profile of stationary modes within an elliptical nanoring. Different regions of the ring were probed and the intensity of the detected modes was in good agreement with that expected from inspection of modes profiles calculated using micromagnetic simulations. The above results prove the superiority of μ-BLS over conventional BLS measurements in the detection of stationary modes, especially those localized close to the edges of the nanorings. There is a price to pay, however, to achieve a so deep lateral resolution. This is the missing of wavevector selectivity, implied by the perpendicular light incidence on the sample surface and the large solid angle of collection of the scattered light.

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4. References

[1] P. S. Keatley, V. V. Kruglyak, A. Neudert, E. A. Galaktionov, R. J. Hicken, J. R. Childress, and J. A. Katine 2008 Phys. Rev. B 78 214412.
[2] V. E. Demidov, S. O. Demokritov, B. Hillebrands, M. Laufenberg, and P. P. Freitas 2004 Appl. Phys. Lett. 85 2866.
[3] Sergej O. Demokritov and Vladislav E. Demidov 2008 IEEE Trans. on Magn. 44 6.
[4] G. Gubbiotti, G. Carlotti, M. Madami, S. Tacchi, P. Vavassori and G. Socino 2009 J. Appl. Phys. 105 07D521.
[5] The axial resolution (depth of focus) is a measurement of how much distance exists behind the objective wherein the sample will remain sharply in focus without loosing contrast.
[6] The calculation of the normal modes frequency and spatial profiles were made by using the OOMMFF code with standard NiFe magnetic parameters (860•10^3 A/m for the saturation magnetization and 1.3•10^-13 J/m for the exchange stiffness constant).
[7] G. Gubbiotti1, M. Madami, S. Tacchi, G. Carlotti M Pasquale, N Singh, S Goolaup and A. O. Adeyeye 2007 J. Phys. Condens. Matter 19 406229.