Nonlinear Hybridization of the Fundamental Eigenmodes of Microscopic Ferromagnetic Ellipses

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We have studied experimentally with high spatial resolution the nonlinear eigenmodes of microscopic Permalloy elliptical elements. We show that the nonlinearity affects the frequencies of the edge and the center modes in an essentially different way. This leads to repulsion of corresponding resonances and to nonlinear mode hybridization resulting in qualitative modifications of the spatial characteristics of the modes. We find that the nonlinear counterparts of the edge and the center modes simultaneously exhibit features specific for both their linear analogues.

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Spectra of eigenmodes of microscopic magnetic structures of different shapes and magnetization conditions have been intensively studied for more than a decade [1–7]. These spectra provide important information and help to understand deeply the microscopic-scale magnetization dynamics, which is of great importance for further development of information-storage and signal-processing technologies [8–11]. Despite the large interest in the topic, most of the studies on eigenmode spectra were limited to the case of low-amplitude magnetic dynamics, whereas the essentially nonlinear large-amplitude dynamics started to attract significant attention only recently [12–14], in particular, owing to its importance for the understanding of spin-transfer-torque [15,16] and microwave-assisted magnetization-switching [17,18] phenomena.

Contrary to the state of the art of the microscopic-scale magnetism, the nonlinear magnetic dynamics in macroscopic-size samples has been studied for a very long time [19]. In particular, it was found that the eigenmodes of macroscopic magnetic-film structures are strongly affected by the nonlinearity [20], which can even lead to an appearance of modes having no analogues in the linear regime [21]. Nevertheless, this knowledge cannot be directly extended to the microscopic scale, since the magnetization dynamics in microscopic structures is strongly affected by finite-size effects, leading to phenomena, which cannot be observed in millimeter-sized samples [1–7] or even lead to nonlinear effects qualitatively opposite to those observed on the macroscopic scale [13].

In this Letter we report on the experimental study of nonlinear eigenmodes of microscopic Permalloy elliptical elements using the recently developed microfocus Brillouin light scattering (BLS) spectroscopy [22] providing submicrometer spatial resolution and enabling a direct mapping of the spatial distributions of the dynamic magnetization of the eigenmodes. We find that the two fundamental eigenmodes of such ferromagnetic elements—the edge and the center mode—show an essentially different nonlinear behavior. With increasing amplitude, the frequency of the edge mode exhibits a continuous positive nonlinear shift, whereas the frequency of the center mode stays unchanged until it is approached by the frequency of the edge mode followed by a nonlinear mode hybridization. We show that this hybridization not only influences the frequencies but also the spatial distributions of the dynamic magnetization of the modes. These distributions lose the shape well known for the linear regime and take a hybrid form.

Figure 1 shows a sketch of the experiment. The studied samples are elliptical elements with lateral dimensions of $1.3 \times 2.4\ \mu m^2$ patterned by *e*-beam lithography and ion beam etching from a 20-nm-thick film of $Ni_{80}Fe_{20}$ (Permalloy). The ellipses are located on top of a 6.2-μm-wide and 200-nm-thick Au microstrip transmission line used for the excitation of the magnetization dynamics. To avoid heating effects the excitation was performed with short pulses of microwave-frequency current with a duration of 100 ns and a repetition period of 2 μs. The dynamic magnetic field h created by the current was perpendicular to the direction of the static magnetic field H applied along the long axis of the ellipses. The static magnetic field was changed in the range from 220 to

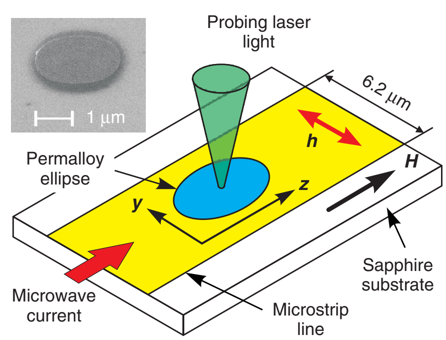

FIG. 1 (color online). Sketch of the experiment. Inset: Image of the Permalloy ellipse recorded by a scanning electron microscope.

1000 Oe. Since no qualitative influence of the field strength on the discussed phenomenon was observed, below we show typical results obtained for $H = 350$ Oe. The local detection of the dynamic magnetization was performed using space- and time-resolved microfocus BLS spectroscopy described in detail elsewhere [23]. The probing light from a single-frequency laser was focused onto the surface of the Permalloy ellipse and the BLS intensity, which is proportional to the square of the amplitude of the dynamic magnetization at the position of the probing spot, was measured.

As is well known (see, e.g., [24]), microscopic thin-film magnetic elements support two types of eigenmodes: dipole-dominated center modes spread over the entire area of the element and exchange-dominated edge modes localized in the narrow spatial regions close to the edges, where the internal static magnetic field is reduced due to demagnetizing effects. In the first step of our experiment we determined the resonant frequencies of these two types of eigenmodes and their dependencies on the peak power P of the excitation signal. Depending on the type of mode, the measurements were performed by placing the probing laser spot either in the middle of the ellipse or at its edge. Then the frequency of the excitation signal was swept and the BLS intensity was recorded. Typical resonant curves obtained for low and high excitation powers are shown in Figs. 2(a) and 2(b), respectively. The power dependencies of the maximum intensity in the corresponding resonances and of the resonant frequencies f_R are presented in Figs. 2(c) and 2(d).

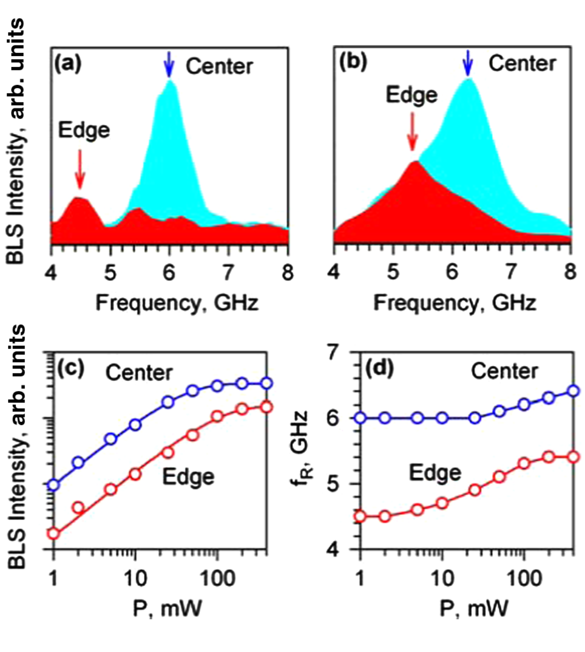

FIG. 2 (color online). (a),(b) Resonant curves of the center and the edge modes for low ($P = 1$ mW) and high ($P = 200$ mW) excitation powers, respectively. (c) Power dependencies of the maximum intensity in the corresponding resonances. (d) Power dependencies of the resonant frequencies determined from the fitting of the resonant curves by the Lorentzian function. Error is smaller than the size of the tokens. $H = 350$ Oe.

From Fig. 2 it is seen that with increasing excitation power the resonances corresponding to both the center and the edge modes become broader and shift toward higher frequencies. The broadening is apparently caused by the increase of the relaxation rate due to the so-called nonlinear damping [12,13], whereas the frequency shift is associated with changes in the projection of the magnetization vector onto the precession axis [19]. The influence of the nonlinear damping on the center and the edge mode is characterized by Fig. 2(c). In the region of small P the resonant intensities of the modes first increase linearly, but, starting from a certain P, show saturation caused by an increase of magnetic losses at high amplitudes of the dynamic magnetization. The saturation of the intensity of the center mode starts at smaller P, which can be associated with its larger excitation efficiency as compared to the edge mode. The data of Fig. 2(c) provide important information about the power thresholds of the nonlinear damping and the relative excitation efficiency of the center and the edge modes and, therefore, can be used as calibration data for the future theoretical analysis.

Let us now analyze the data of Fig. 2(d) characterizing the nonlinear frequency shift of the two modes. From this figure it is seen that the center and the edge modes are affected by the nonlinearity in a qualitatively different way. The resonant frequency of the edge mode experiences a noticeable shift already for relatively small excitation powers, whereas the frequency of the center mode stays unchanged up to $P \approx 25$ mW. As the frequency of the edge mode approaches that of the center mode, the latter starts to increase. Simultaneously, the frequency of the edge mode shows saturation and completely stops growing at $P \approx 200$ mW. Such a behavior can be treated as a "repulsion" of resonances preventing them from degeneration—a phenomenon which can be found in many physical systems of different nature. In particular, in magnetic systems, the repulsion of dispersion curves was found in the linear spectrum of propagating spin-wave modes (see, e.g., [25]). The principal difference of the phenomenon observed here is that it does not exist in the small-amplitude linear regime, but appears as a result of the reaction of the system on the increased oscillation amplitude.

Usually, the repulsion of resonances is accompanied by a hybridization of the resonant states, leading to qualitative changes in their spatial characteristics. In order to address this issue for the magnetic eigenmodes, we measured two-dimensional maps of the BLS intensity corresponding to the center and the edge modes for different excitation powers. Typical results of these measurements are presented in Fig. 3. Figures 3(a) and 3(b) show the maps obtained in the small-amplitude linear regime ($P = 1$ mW), whereas Figs. 3(c) and 3(d) show the maps recorded in the nonlinear regime ($P = 400$ mW), corresponding to the region of the strong repulsion of the resonant frequencies. As seen from Figs. 3(a) and 3(b), in the linear regime the two modes exhibit well-known spatial distributions of the dynamic magnetization: the center mode shows a bell-like shape with nearly half-sine profiles in both y and z directions, whereas the edge mode shows narrow intensity peaks strongly localized at the edges of the Permalloy ellipse. At large P [see Figs. 3(c) and 3(d)] the spatial distributions corresponding to the modes appear to be rather different from the linear ones. The distribution for the center mode is elongated in the direction of the static magnetic field and cannot be described by simple harmonic functions anymore. The distribution for the edge mode demonstrates a shift of the intensity peaks toward the middle of the ellipse and their widening, i.e., a weakening of the spatial localization. In other words, with the increase of P the center mode tends to occupy the edge regions, whereas the edge mode tends to occupy the center region of the elliptical element, which can be considered as a formation of new hybrid eigenmodes, each of them exhibiting features specific for both center and edge modes. In fact, each of these hybrid nonlinear eigenmodes represents a bundle of linear modes coupled to each other due to the nonlinear interaction. Nevertheless, one can clearly associate a particular nonlinear eigenmode with a linear one by determining which linear eigenmode it evolves from.

Figure 4 shows the normalized z profiles of the edge mode recorded for three different values of the excitation power ($P = 1$, 50, and 400 mW). Despite the fact that the width of the edge mode profile is comparable to the spatial resolution of the microfocus BLS technique (≈ 250 nm), one can estimate from Fig. 4 the main quantitative characteristics of the nonlinear modification of this mode. For small P the mode is strongly localized (the width is about 0.4 μm) and its maximum is located at a distance of about 0.2 μm from the edge of the ellipse ($z = 0$). As P increases, the localization area becomes wider and the maximum shifts toward the middle of the ellipse ($z = 1.2$ μm) reaching a distance from the edge of about 0.4 μm at $P = 400$ mW. Simultaneously, the dynamic magnetization in the middle of the ellipse increases and becomes comparable to the intensity in the edge regions at large P.

Precise quantitative characterization of the hybridization process can be done by analyzing the spatial distributions corresponding to the center mode, which can be accurately imaged with the available spatial resolution. Figures 5(a) and 5(b) show the normalized z and y profiles of the center mode recorded for excitation powers of 1, 50, and 400 mW. As seen from Figs. 5(a) and 5(b), the y profiles of the center mode are practically independent of P, whereas the z profiles demonstrate a widening by about a factor of 1.7 and show at large powers a decrease of the intensity in the middle of the ellipse and a formation of two maxima shifted toward the edges, which are characteristic features of the linear-regime edge mode. The power dependencies of the spatial width of the z and y profiles in Fig. 5(c) quantitatively characterize the nonlinear changes in the mode spatial distributions. As seen from the figure, the y width stays equal to about 1 μm in a wide range of P from 1 to 100 mW and then slightly decreases to about 0.8 μm. In contrast, the z width keeps its linear value of 1.2 μm in the range $P = 1$–10 mW only, and then starts quickly to increase, reaching a value of about 1.9 μm for $P = 400$ mW. Note that the power at which the z profile of the center mode starts to expand agrees well with the power at which the repulsion of the resonances starts. This confirms that these two phenomena are closely connected and represent a single hybridization process.

In conclusion, we have shown that the well-known linear eigenmodes of microscopic magnetic elements can be significantly affected by the nonlinearity. The nonlinearity

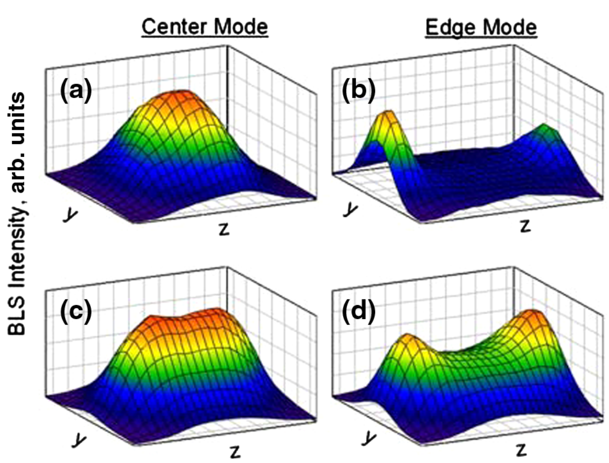

FIG. 3 (color online). Two-dimensional maps of the BLS intensity proportional to the square of the amplitude of the dynamic magnetization. The maps have lateral dimensions of 1.4×2.4 μm^2 in the y and z direction, respectively, and were recorded with a spatial step size of 0.1 μm. (a),(b) Maps for the center and the edge modes in the small-amplitude linear regime ($P = 1$ mW). (c),(d) Maps for the same modes recorded in the nonlinear regime ($P = 400$ mW). $H = 350$ Oe.

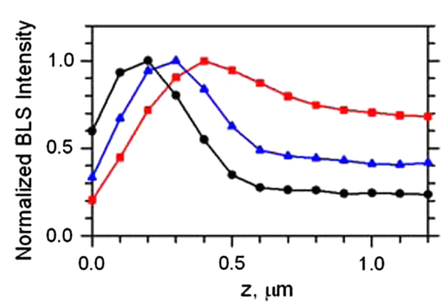

FIG. 4 (color online). z profiles of the edge mode recorded for three different values of the excitation power: $P = 1$ mW (circles), $P = 50$ mW (triangles), and $P = 400$ mW (squares). The data are normalized at the position of the maximum intensity for the convenience of comparison.

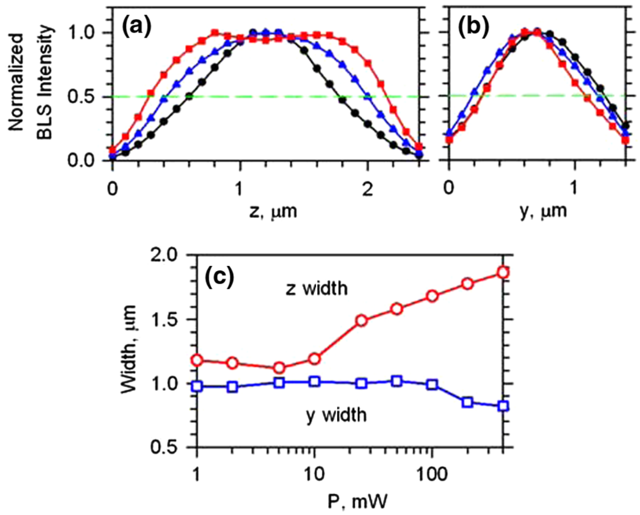

FIG. 5 (color online). (a) z and (b) y profiles of the center mode recorded for excitation powers $P = 1$ mW (circles), $P = 50$ mW (triangles), and $P = 400$ mW (squares). The data are normalized at the position of the maximum intensity for the convenience of comparison. (c) Power dependencies of the spatial width of the z and y profiles, measured at one-half of the maximum intensity.

results not only in quantitative changes, such as an increased damping and a frequency shift, but also in qualitative modifications of the eigenmodes. We find that the fundamental modes, which are almost independent of each other in the linear regime, start to interact strongly in the nonlinear regime and create a new set of hybrid modes, which are not purely edge or center modes anymore. Despite the fact that the phenomenon of the mode hybridization appears to be general, its quantitative characteristics are expected to depend on geometrical and material parameters of the microscopic magnetic elements. Therefore, its deep understanding demands further detailed experimental and theoretical investigations. We believe that our findings will stimulate such activities resulting in better understanding of large-amplitude dynamic magnetic phenomena and their role in magnetic signal-processing and data-storage devices.

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