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Spin wave localization in ferromagnetic layer induced by superconducting nanostructure

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The stray field produced by superconducting nanostructure can be controlled by the external magnetic field and affect the magnetization dynamics in the magnetic system placed in its range. In the case of a hybrid system consisting of a superconducting strip placed over a magnetic layer, we predict theoretically the confinement of spin waves in the well of the static stray field. The number of bound states and their frequencies can be controlled by an external magnetic field. We have presented the results of semi-analytical calculations complemented by numerical computations.

***Index Terms* — hybrid structure, localization, spin waves, superconductors.**

I. Introduction

The hybrid systems [1,2], where the superconductor (SC) and the ferromagnet (FM) are part of the same structure and interact with each other, usually offer much more flexibility both in design and implementation of new features that exotic materials which combines the ferromagnetic and superconducting properties [3]. One of the topics not fully explored is the problem of localization of spin waves in these systems. In this study, we conduct a theoretical and numerical investigation of the confinement of dipolar-exchange spin waves (SW), induced in a uniform magnetic layer by the stray field of a SC strip. The detailed description of these investigations is presented in our manuscript [4].

II. Model

The considered hybrid system consists of gallium-doped yttrium iron garnet (Ga:YIG) ferrimagnetic thin film and Nb superconducting (SC) stripe in Meissner state, separated by thin nonmagnetic spacer (Fig. 1). According to the Meissner effect, a SC strip expels a magnetic field from its volume by means of eddy currents. These currents create a non-uniform distribution of the magnetic field throughout the entire space, including the FM film. Such geometry enables the investigation of the coupling between FM and SC subsystems as purely classical, where the stray magnetic field from the eddy currents in SC stripe impacts the magnetization in FM layer. The system is placed in an external magnetic field perpendicular B_0 to the FM layer. In Ga:YIG, the shape anisotropy is overcome by the perpendicular magnetic anisotropy (PMA), leading to the magnetization being directed out of plane even in the absence of external magnetic field. Operating with the relatively small external field, we can sustain the Meissner state in confined geometry of the stripe, and observe the impact of the stray field of SC stripe on the magnetization dynamics in FM layer. Then, the stray field of SC strip is tuned by the external field and induces the well of static effective field of controllable depth in the FM layer. The well can confine the spin waves of the frequencies lower than the FMR frequency of FM layer in the absence of SC strip. A uniformly-magnetized infinite FM layer does not produce outside any static stray field. However, the stray field of SC strip induces weak magnetization texture in FM layer, close to SC strip edges. It can produce a static stray field, although it is small and can be neglected. Therefore, there is no need to solve self-consistent problem for our system and take into account the mutual interaction between the FM layer and the SC strip.

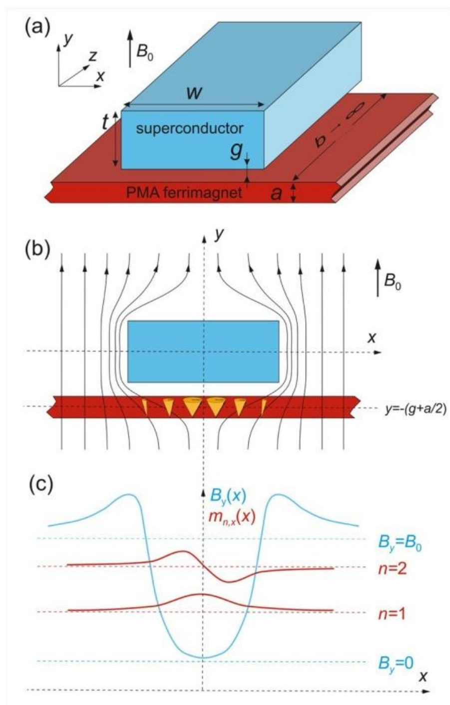

Fig. 1. (a) A thin magnetic film is exposed to the stray field of a rectangular superconducting strip. The FM and the SC are separated by a small gap. The hand-drawn sketches (a,b) illustrate the mechanism of SW localization. (b) The static internal magnetic field is lowered in the region of the FM underneath the SC. This leads to the confinement of spin-wave modes, (c) which are quantized in the quasiparabolic well of the internal field.

Taking these assumptions into account, our studies were carried out in two stages. We first calculated the static stray field generated by the SC strip. It was determined from the distribution of superconducting currents, which was found by semi-analytical solution of the London equations using method developed in [5]. The static field generated by SC stripe was then included as a correction to the effective field to Landau-Lifshitz (LL) equation. The LL equation was solved both semi-analytically and numerically and was used to find the confined spin-wave modes.

III. RESULTS

We considered SC strip of the thickness t = 100 nm and width w = 400 (or 800 nm, for comparison) with the London penetration depth λ = 50 nm. The SC strip was placed over the FM layer, separated from its top surface by the spacer of thickness g = 10 nm; the layer's thickness was a = 20 nm (Fig. 1). The FM layer, made of Ga:YIG, was characterized by the following values of material parameters: saturation magnetization M_s = 16 kA/m, exchange stiffness A_{ex} = 1.37 pJ/m and gyromagnetic ratio γ = 179 GHz/T, anisotropy K_u = 756 J/m^3. The profiles of the y- and x-components of stray field B_{sc} produced by SC strip was calculated in the middle the FM film for two selected values of out-of-plane applied field B_0 = 30 mT and 90 mT. The well of $B_{sc,y}(x)$ is a signature of the screening of external field by the cost of the increase of field close to the edges of the stripe. On the other hand, the in-plane component of the stray field $B_{sc,x}(x)$ reflects the deflection of the magnetic field lines by-passing the SC stripe. The stray field B_{sc} was calculated semi-analytically and obtained results was successfully cross-checked using Finite Element Method calculations. The field B_{sc} is linearly scalable with the external field B_0. While we increase B_0 from 30 mT to 90 mT, the magnitude of the profiles $B_{sc,y}(x)$, $B_{sc,x}(x)$ is increasing exactly there times. In the absence of SC strip, the static magnetization is oriented out-of-plane due to perpendicular anisotropy in Ga:YIG layer. But the in-plane component $B_{sc,x}(x)$ tilts magnetization from the layer's normal. Surprisingly, the angle between magnetization and the applied field's direction increases with the increase of the magnitude of applied field. However, it is understandable if we keep in mind that the in-plane component of the stray field increases with the applied field. It should be noted that the formation of non-collinear magnetization texture allowing for the SWs excitation by alternating magnetic field applied along external static field B_0. In this case, the spin wave modes will only be excited in the regions below the edges of the SC stripes, where the static magnetization is tilted.

The dependence of frequencies of the localized SW modes on the external magnetic field is presented on the Fig. 2, for the SC strip width w = 400 nm (Fig. 2(a)) and 800 nm (Fig. 2(b)). The results of semi-analytical calculations and micromagnetic simulations are marked by solid lines and dots, respectively. The dashed blue lines show the ferromagnetic resonance (FMR) frequency of the homogeneously magnetized film. The number of localized modes rises with increasing external field value as a result of deeper well $B_{sc,x}(x)$. Also, we observe a larger number of localized SW modes for wider stripe, what is caused by two factors: (i) the frequency difference between SW modes energy levels becomes smaller due to the widening of the well (the main factor), and (ii) the depth of the well is slightly increased with the widening of SC strip. In general, the results of theoretical calculations and micromagnetic simulations are in good agreement. The discrepancies are larger for the strip width and they increase with increasing external magnetic field. This can be related to the simplifications underlying our theoretical model, according to which we have neglected the tangential component of the field produced by the SC stripe $B_{sc,x}$, which slightly deflects the static magnetization a from the normal to the FM layer in the vicinity of the SC stripe edges. To be clear, we have considered the uniform magnetization ground state where the FM layer is magnetized out of plane. This assumption is reasonable because the magnetization deviation angle is relatively small for a narrow strip, while for a wider strip the deviation angle is larger and increases significantly for large external field values.

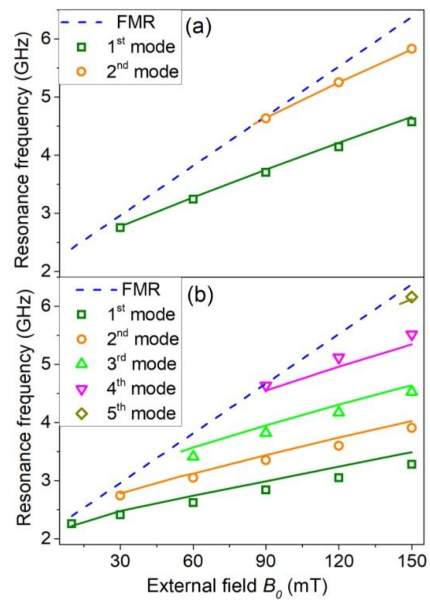

Fig. 2. The dependence of the localized SW modes on the external magnetic field B_0 for the system with stripes width w = 400 nm (a) and w = 800 nm (b). The solid lines and square dots correspond to the semi-analytical theory and micromagnetic simulations respectively. Dashed lines shows FMR frequency of uniformly magnetized film.

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