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| **First Author Gubbiotti**Specific Order of Authorship in Table CellsACM, New York, NYgubbiotti@corporation.com | **Second Author Pam Malagò**Dipartimento di Fisica e GeologiaP.O. Box 6221, Italymalago@affiliation.org |
| **Third Author Fin**Dipartimento di Fisica e ScienzeP.O. Box 5000, Italyfin@affiliation.org | **Fourth (4th) Author Tacchi**Dipartimento di Fisica e GeologiaP.O. Box 6221, Italytacchi@affiliation.org |
| **Fifth Author 5. Giovannini**Dipartimento di Fisica e GeologiaP.O. Box 6221, Italygiovannini@affiliation.org | **Sixth 6. Madami****Seventh Author** **Ram**Dipartimento di Fisica e GeologiaP.O. Box 6221, Italymadami@affiliation.org |

ABSTRACT

Two-dimensional[[1]](#footnote-2) arrays of bi-component structures made of cobalt and permalloy elliptical dots with thickness of 25 nm. To continue with your abstract text, authors will need to manually include the balance of text into column 2 on the next page. Use a good breaking point (like an end of a sentence). Abstracts should be about 150 words. Required.

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Brillouin light scattering has been exploited to study the frequency dependence of thermally excited magnetic eigenmodes on the intensity of the external magnetic field, applied along the easy axis of the elements.

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1 INTRODUCTION (MAIN SECTION HEADS ~ ALL CAPS)

In the last decade, there has been an intense research activity in studying the spectrum of magnetic eigenmodes both in single and multi-layered confined magnetic elements with different shape and lateral dimensions [[1](#bib1)–[3](#bib3)]. This interest has been further renewed by the emergence of the spin-transfer torque effect, where a spin-polarized current can drive microwave frequency dynamics of such magnetic elements into steady-state precessional oscillations. Moreover, the knowledge of the magnetic eigenmodes is very important also from a fundamental point of view for probing the intrinsic dynamic properties of the nanoparticles. Besides, dense arrays of magnetic elements have been extensively studied in the field of Magnonic Crystals (MCs), that is magnetic media with periodic modulation of the magnetic parameters, for their capability to support the propagation of collective spin waves [[4](#bib4),[5](#bib5)]. It has been demonstrated that in MCs the spin wave dispersion is characterized by magnonic band gaps, i.e. a similar feature was already found in simple two-dimensional lattices with equal elements like, for example, in two or four-sublattice antiferromagnets and in two-sublattice antiferromagnets in the presence of a spin-flop transition. In addition to this, complex periodic arrays of dipolarly coupled magnetic dots are of special interest because they can support the propagation of non-reciprocal spin waves, i.e. ((*k*) ≠ (−*k*)), where  is the angular frequency and *k* is a wave vector, which could find application in the signal transmission and information processing as well as in the design of microwave isolators and circulators.



Figure 1: MOKE hysteresis loop for the bi-component Py/Co dots array measured along the dots long axis.

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**Table 1:** Frequency of Special Characters

|  |  |  |
| --- | --- | --- |
| *Non-English or Math* | *Frequency* | *Comments* |
| Ø | 1 in 1,000 | For Swedish names |
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| Ø2 | 2 in 1,000 | For Swedish names |
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| Ø3 |  |  |

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For each micromagnetic cell the reduced magnetization takes the form where themagnetization (saturation magnetization) in the *k-*th cell; note that the saturation magnetization now depends on the ferromagnetic material through the index *k*. Hence, in a polar reference frame

|  |  |
| --- | --- |
| $$\left(x+a\right)^{n}=\sum\_{k=0}^{n}\left(\genfrac{}{}{0pt}{}{n}{k}\right)x^{k}a^{n-k}$$ | (1) |

where $K$ is the azimuthal (polar) angle of the magnetization (the time dependence is omitted). The second derivatives of the energy density depend on the micromagnetic cell indexes, and through them on the material index corresponding either to Py or Co.

It is possible to write the following periodicity rule valid for the dynamic magnetization $δm(r)$ of each collective mode, a version of the Bloch theorem, viz. Note that, exchange contribution is set equal to zero, because in each unit cell the two elliptical dots are separated. Moreover, the uniaxial anisotropy energy density of Co is neglected [Table 1](#tb1).

|  |  |
| --- | --- |
| $$x=\frac{-b\pm \sqrt{b^{2}-4ac}}{2a}$$ | (2) |

Therefore one can observe either an in-phase (acoustic) or an out-of-phase (optical) character of the modes, with respect to the precession of the in-plane magnetization components in adjacent Py and Co dots.



Figure 2: MFM images of the bi-component Py/Co dots for different values of the applied magnetic field which are indicated by greek letters along both the major and minor hysteresis loop.

We would like to mention that the DMM presents several advantages with respect to OOMMF for calculating the spectrum of magnetic eigenmodes for the following reasons: *a*) There is no need to excite the system by any magnetic field pulse, *b)* A single calculation llows to determine the frequencies and eigenvectors of all spin-wave modes of any symmetry, *c*) The spectrum is computed directly in the frequency domain, *d*) The mode degeneracy is successfully solved, *e*) The spatial profiles of the spin-wave modes are directly determined as eigenvectors and, finally, *f*) The differential scattering cross-section can be calculated accurately from the eigenvectors associated to each spin-wave mode. This is a clear indication that both the Py and Co sub-elements are in a single domain state where Py and Co magnetizations are all oriented with their magnetic moment along the chain and field direction. At point ** (*H* = −372 Oe) of the hysteresis loop, where the plateau is observed in the *M*-*H* loop, the dark and bright spots of the Py dots are reversed with respect to those of Co, accounting for an antiparallel relative alignment of magnetization.

3 RESULTS AND DISCUSSION

3.1 Magnetization Curves and MFM Characterization

The major hysteresis loop measured by MOKE, plotted in [Fig. 1](#fig1), displays a two-step switching process due to the distinct magnetization reversal of the Py and Co sub-elements, characterized by a different coercivity. We performed a field-dependent MFM analysis whose main results are reported in [Fig. 2](#fig2). At large positive field (*H*= +800 Oe, not shown here) and at remanence (** point of the hysteresis loop of [Fig. 1](#fig1)), the structures are characterized by a strong dipolar contrast due to the stray fields emanated from both the Py and Co dots.

We have also used MFM to measure the magnetic configurations along the minor hysteresis loop, described above. Once the AP ground state has been generated at *H*= −500 Oe, the applied field is increased in the positive direction. The MFM image taken at point of [Fig. 2](#fig2), remanent state of the minor loop (*H* = 0), shows that the AP state is stable and remains unchanged until the magnetic field is increased up to +300 Oe where the Py magnetization reverses its orientation and returns to be aligned with that of Co dots. On the basis of the above MFM investigation, one can say that the structures are always in a single domain state, while the relative magnetization orientation between the adjacent Py and Co elements depends on both the field value and the sample history.



Figure 3: Dependence of the magnetic eigeinmode wave frequency on the applied field strength.



Figure 4: Calculated spatial distribution of the in-plane dynamic magnetization.

3.2 Field Dependent BLS Measurements and DMM Calculations

[Fig. 3](#fig3) displays the frequencies of BLS peaks plotted as a function of the applied field magnitude starting from positive values. The field is then decreased and reversed following the upper branch of the hysteresis loop, shown in the same figure. Up to five peaks are measured in the spectra, as shown in spectrum measured at H = 0 Oe in the [Fig. 3](#fig3) inset, and their field evolution analyzed over the whole field range investigated. The detected modes are identified and labeled on the basis of their calculated spatial profiles, shown in [Fig. 4](#fig4) for *H*= 500 and −500 Oe. They exhibit marked localization into either the Co or the Py dots, as stated at the end of the previous Section, were it was introduced the labelling notation containing the dominant localization region (either Py or Co) and the spatial symmetry (EM, F, DE, etc).

When the dots are in the P state, up to five modes were detected in BLS spectra. On the basis of the calculated profiles (right panel of [Fig. 4](#fig4)), we identified in the P state the two modes at lowest frequencies as the EM(Py) and the F(Py), with a very small spin precession amplitude into the Co dot. This is because for this material we are below the frequency threshold for the existence of spin waves. A similar effect has been observed in periodic array of alternating Permalloy and Co nanostripes

Note that the nodal lines present in the spatial profile of the F (Co) mode perpendicular to the long axis of the ellipse do not correspond to a real change of sign of the dynamic magnetization and are due to the partial hybridization of the F mode with higher-order modes having frequencies close to the one of the F mode. Interestingly, the frequency slope of modes localized into the Co dots is larger than that of Py modes, due to larger values of the Co magnetization and gyromagnetic ratio. An overall good agreement between the calculated (dotted curves) and measured frequency (full points) has been achieved (see [Fig. 3](#fig3)) even if some discrepancies are observed for the frequency of the EM and 1DE (Py) modes.

The corresponding spatial profiles of the modes are shown in the left panels of [Fig. 4](#fig4). Here one can see that the only mode which is purely localized in one dot is the EM of Co, because now it is sub-threshold for Py. A further reduction of *H*, which is sufficient to cause the Co magnetization reversal, produces a P state at negative fields and the frequency starts to increase again as a function of the applied field. In this field range the frequencies of modes in the Py dots monotonously increase in a way similar to that measured in the P state for positive field values while an abrupt change in the frequency of Co modes occurs.



Figure 5: Full point are the frequencies measured along the minor hysteresis.

Table 2: Comparison of Coefficients from Atomistic

|  |  |  |
| --- | --- | --- |
| *Atm* | *MS-CG* | *MS-CG/DPD* |
| 1.78 | 14.32 | 1.74 (−2%) |
| 0.43 | 31.00 | 0.40 (−7%) |
| 0.062 | 15.61 | 0.048 (−23%) |
| 0.032 | 9.76 | 0.024 (−24%) |
| 0.020 | 4.66 | 0.015 (−25%) |
| 0.012 | 2.32 | -"- |
| 0.0076 | 0.016 | -"- |

In [Fig. 5](#fig5) we show the modes frequency measured along the minor loop (full points) and compare them with values measured along the major M-H loop (open points).

The reason of this complex behavior will be addressed in the following, analyzing the interplay of both static and dynamic dipolar coupling between the adjacent Py and Co dots [Table 2](#tb2).

4 CONCLUSIONS

In summary, we have performed both an experimental and theoretical study of the spin eigenmodes in dipolarly coupled bi-component cobalt and permalloy elliptical nanodots. Several eigenmodes have been identified and their frequency evolution as a function of the intensity of the applied magnetic field has been measured by Brillouin light scattering technique, encompassing the ground states where the cobalt and permalloy dots magnetizations are parallel or anti-parallel, respectively.

ACKNOWLEDGMENTS

This work was partially supported by the MIUR-PRIN 2010–11 Project 2010ECA8P3 “DyNanoMag” and by the National Research Foundation, Prime Minister's office, Singapore under its Competitive Research Programme (CRP Award No. NRF-CRP 10-2012-03).

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CHI’19 Extended Abstracts, May 4-9, 2019, Glagsgow, Scotland, UK.

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ACM ISBN 978-1-4503-5971-9/19/05.

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