Magnonic and phononic properties of inverse opal structures

A.A. Stashkevich[1], M.P. Kostylev[2], Y. Roussigné[1], N.A. Grigoryeva[3], A.A. Mistonov[3], D. Menzel[4], N.A. Sapoletova[5], K.S. Napolskii[5], A.A. Eliseev[5], A.V. Lukashin[5], S.V. Grigoriev[6], L. Belliard[7], B.Bonello[7], Ph. Djemia[1]

[1]LSPM CNRS (UPR 3407), Université Paris 13, 93430 Villetaneuse, France
stachkevitch@univ-paris13.fr
[2]School of Physics M013, the University of Western Australia, Crawley 6009 WA, Australia
[3]Saint Petersburg State University, 199034, Saint Petersburg, Russia
[4]Institute of Condensed Matter Physics, 308108 Braunschweig, Germany
[5]Lomonosov Moscow State University, 119992 Moscow, Russia
[6]Petersburg Nuclear Physics Institute, Gatchina, 188300 St.Petersburg, Russia
[7]Institut des NanoSciences de Paris (INSP), UMR CNRS 7588, Université Pierre et Marie Curie, 75015 Paris, France

Abstract

In this paper we report on both magnonic and phononic properties of a Ni-based inverse ferromagnetic opal film with the [111] axis of fcc structure along the normal to the film. FMR (FerroMagnetic Resonance) measurements have revealed multiple spin wave (SW) resonances for the magnetic field applied perpendicular to the film. For the field applied in the film plane a broad band of microwave absorption is observed which does not contain a fine structure. Theoretical analysis allows concluding that SW resonanaces localised on chains of quasi-tetrahedron – quasi-cube – quasi-tetrahedron basic elements are weakly coupled, which excludes pronounced collective "magnonic" behavior. On the contrary, our preliminary "pump-probe" experimental studies of acoustic properties of such structures have revealed a presence of Bloch-type phonons.

1. Introduction

Rapid progress in photonics, exploiting unusual wave properties of optical waves in structures with a submicron periodic modulation of the refractive index has lead to creation of a new type of materials known as photonic crystals [1]. The latter demonstrate such prominent features as Brillouin zones (BZ), whose emergence is accompanied by a number of unique peculiarities in wave behavior, typically occurring in the vicinity of BZ boundaries, which include photonic bandgaps, slow light propagation, and negative dispersion.

The universal nature of wave physics in periodic media dictates striking analogies between photonics and magnonics [2,3]. In the case of magnonics spin waves in periodic ferromagnetic structures (magnonic crystals) are exploited. Similarly, phononic behaviour is possible in artificial media with periodically modulated elastic properties.

Artificial opals are ideally suited for applications as photonic, magnonic and phononic crystals. While there exists extensive literature dedicated to studies of 3D photonic effects in direct opals (see, for example, Ref. [4] and references herein), wave processes in inverse opal structures are far less investigated. At the same time, the technologies involved in their fabrication allow one creation of 3D periodic ferromagnetic structures, which makes them extremely promising as 3D magnonic and phononic materials.

ISBN 978-952-67611-2-1

2. Experiment and discussion

A nickel inverse opal (IO) sample was fabricated by using electrodeposition technique and utilizing a colloidal crystal film as a template. The colloidal crystal film was prepared by an electric-field-assisted vertical deposition of monodisperse polystyrene microspheres (D = 530 nm; RSD < 10 %) onto a Si(100) wafer coated with a 100 nm-thick gold layer [5]. According to the results of SEM, the average center-to-center distances between spherical voids are 515 ± 10 nm (see Fig.1). The high-resolution X-ray diffraction shows that IO typically have the face centered cubic (fcc) structure with a small amount of stacking faults along the <111> axes.

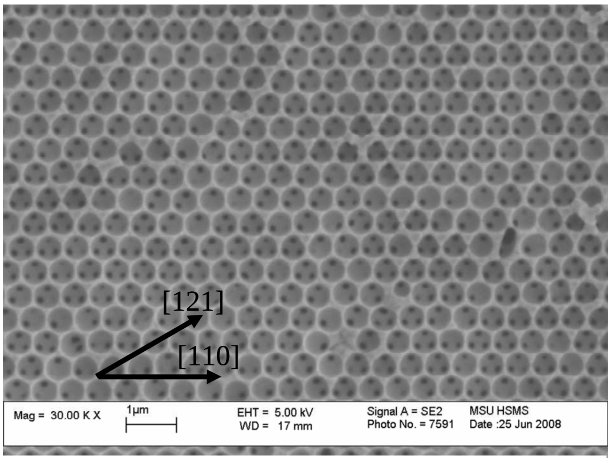

Fig.1. Top view SEM image of the Ni inverse opal.

In our broadband FMR experiments we use a microwave generator to apply a microwave signal to a section of a microstrip line. The sample sits on top of this microstrip transducer, whose width is 1.5 mm. Microwave absorption spectra are measured at a number of fixed frequencies ranging from 2 GHz up to 18 GHz, while the magnetic field is swept very slowly (with a period of 30 min) from -8000 Oe to 8000 Oe. Typical results, in the out-of-plane geometry, are presented in Fig.2. Experimental FMR data are given with dots. The thick solid line represents the fit of the fundamental (Kittel) mode with the theory of effective cylinders. Thin solid lines reproduce respective parts of the hysteresis loops. For better understanding, in the inset is given the complete hysteresis loop.

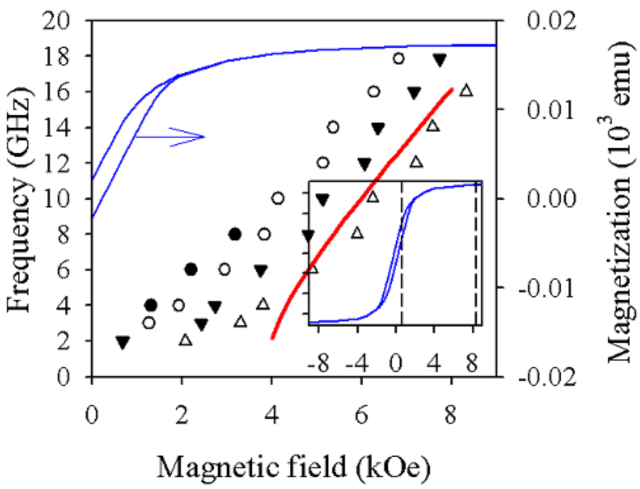

Fig.2. FMR results in the out-of-plane geometry.

The basic element of the studied IO structure is the chain quasi-tetrahedron – quasi-cube – quasi-tetrahedron (T-C-T). These chains run along the <111> directions. We suggest that the collective motion of these chains may be approximated with dynamics of long cylinders of nanoscale cross-sections. We justify this assumption by the fact that the results obtained in the in-plane geometry display a feature known as a characteristic signature of the presence of structural elements with a pronounced uniaxial anisotropy, for example cylinders, when magnetized along the easy axis: there is no signal at low frequencies. This agrees well with the results of static characterization that has revealed a major role played by chains of cubes and therahedrons, in the magnetic behavior of IO structures.

Interestingly, an alternative theoretical model, based on the continuous film approach, can be also proposed. Although being more speculative because of being based on a larger number of assumptions, the cylinder based theory has got one important advantage with respect to the model of the effective continuous film: it provides a natural explanation for the multi-modal character of the FMR spectrum seen in the out-of-plane field configuration (Fig. 2). In the framework of this model, the mode frequency splitting Δf can be regarded as an important feature which characterizes the studied magnetic structure. The higher-order FMR modes of a cylinder are not spatially uniform and taking

ISBN 978-952-67611-2-1

into account the inhomogeneous exchange interaction is necessary. According to our experimental results Δf is of the order of approximately 3 GHz. In our estimations we relied on the theory for an infinite isolated cylinder elaborated in Ref. [6]. Assuming the oscillation of the magnetization is uniform along the cylinder axis, each eigen-mode, as in any cylindric waveguide, is characterized by two indices: *"n"* and *"p"*. The first one originates from radial and azimuthal profiles, expressed in terms of Bessel functions of *"n-th"* order and $exp(in\theta)$, respectively, while the second one is introduced to label the rank *"p"* of the corresponding radial solution for given boundary conditions. Our calculations, performed for two values of the saturating magnetic field, H = 4000 Oe and H = 8000 Oe, show that the frequency splitting $\Delta f \approx 3$ GHz for lower modes (n = 0, p = 1,2,3,4) is best fitted if the cylinder radius is set R = 90 nm, which corresponds rather well to the actual size of the basic element. Our theoretical estimations have shown that dipolar inter-cylinder interactions play an insignificant role and, thus, the Bloch features are not pronounced.

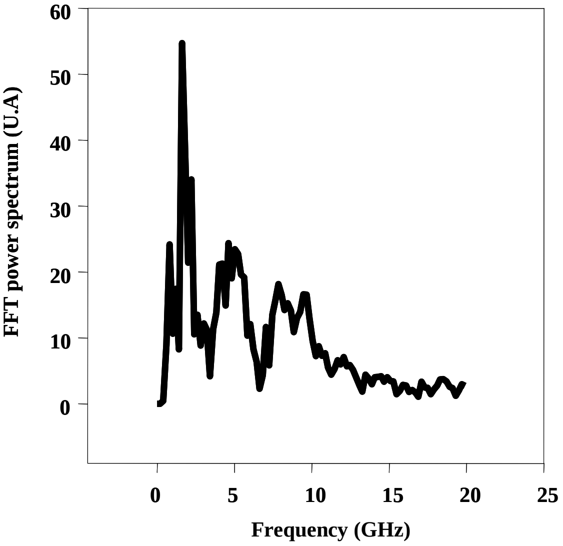

Fig.3. FFT power spectrum of acoustic phonons localised on an IO structure.

On the contrary, our experimental investigations, carried out in the similar frequency range (0 – 20 GHz), of acoustic modes, performed with the pump-probe picoseconds ultrasonic technique [7], clearly manifest a presence of bandgaps (Fig. 3), a characteristic signature of phononic Bloch type wave behaviour. There positions agree well theoretical predictions.

3. Conclusion

In this work we have carried out experimental studies of magnetic and elastic dynamic response of a ferromagnetic inverse opal made from nickel. Our investigation revealed in the magnetic case a SW localised on basic elements, weakly coupled via inter-element dipolar interactions. At the same time, acoustic behaviour is described by pronounced phononic features.

References

[1] K. Sakoda, *Optical Properties of Photonic Crystals*, Berlin: Springer, 2001.
[2] M.P.Kostylev, A.A.Stashkevich, and N.A.Sergeeva, *Physical Review B*, vol.69, p. 064408, 2004.
[3] V. V. Kruglyak, S. O.Demokritov, and D. Grundler, *J. Phys. D.: Appl. Phys*, vol. 43, p. 264001, 2010.
[4] V.G. Golubev, Three-Dimensional Photonic Crystals Based on Opal-Semiconductor and Opal-Metal Nanocomposites, in *Advanced Materials and Technologies for Micro/Nano-Devices, Sensors and Actuators (E. Gusev et al. (Eds.))*, © Springer Science + Business Media B.V., 2010.
[5] K.S. Napolskii, N.A. Sapoletova, D.F. Gorozhankin, A.A. Eliseev, A.V. Petukhov, D.V. Byelov, A.A. Mistonov, N.A. Grigoryeva, W.G. Bouwman, K.O. Kvashnina, A.A. Snigirev, D.Yu. Chernyshov, A.V. Vassilieva, S.V. Grigoriev, *Langmuir*, vol. 26(4), p. 2346 (PS), 2010.
[6] R. Arias, D.L. Mills, *Physical Review B*, vol. 63, p. 134439, 2001.
[7] J. Pierre, O. Boyko, L. Belliard, J. O. Vasseur, B. Bonello, *Appl. Phys. Lett*., vol.97, p. 121919, 2010.