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Electromagnetic sensors based on magnonic crystals for applications in the fields of biomedical and NDT

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Abstract

An exploratory investigation of high sensitivity sensors based on magnonic crystals for the measurement of weak magnetic fields at room temperature is presented. The samples are YIG crystals on GGG substrate (Gadolinium-Gallium-Garnet) on which a periodic structure of shallow grooves are etched or gold stripes are deposited. The excitation of surface magnetostatic spin waves (MSSW) which should appear in these structures is obtained by means of microstrip transmission line or microstrip planar antenna.

The measurement of the magnonic structure by complex transmission coefficient (S_{12}) shows a significant shift in frequency of the maximum absorption peak related to magnonic band gap which depends on the magnitude of the DC magnetic bias field applied. It shows the possibility of magnonic high Q-value band gap implementation with respect to spin wave propagation band (GHz band) in magnonic crystals applied to spin waves detection of magnetic fields.

The influence of the characteristics of the microstrip line or the microstrip antenna on sensor performance (sensitivity and resolution) is studied.

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Keywords : Magnonic crystals, Magnetic field sensor, YIG film, Magnetostatic surface wave (MSSW), Band gap

1. Introduction

The highly sensitive detection of magnetic weak fields, especially at room temperature, has always attracted considerable attention, mostly in medical sciences and engineering applications as in medical imaging or Non Destructive Testing (NDT).

In the past, various types of magnetic field sensors have been proposed but their device applications were often limited by constraints such as size, weight, performance and cost. Today, the technology of magnetic fields sensing has evolved through the need for improved sensitivity, lower noise, higher operating speed, smaller size, weight and cost. Recent studies have shown that a new type of high sensitive magnetic field sensor could be performed using a magnonic crystal (MC) [1,2].

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Magnonic crystals are a new class of artificial magnetic materials embodying propagation of magnetic waves. They are characterised by a medium whose magnetic properties are periodically spatially modulated and where collective spin waves can propagate [2]. Periodicity results in a magnetic band structure (stop band) in the spin-wave dispersion [3] for magnons (the quanta of spin waves) with allowed and forbidden frequency values.

This structure might act as a reflector, owing to Bragg reflection at Brillouin zone edges, whenever the artificial periodicity matches the wavelength of spin waves. During propagation along such periodic structure, the spin wave group velocity changes, which can lead to scattering of surface waves. Furthermore, it is known that stop bands observed in magnonic crystal corresponds to propagation of magnetic waves supported either by magnetostatic coupling or exchange coupling of spins, depending on the wavelength of the spin waves (magnetostatic regime is for 1 µm or larger and exchange is for 1 nm or less). Since the wavelength of spin waves is shorter than that of electromagnetic waves in the gigahertz frequency range, magnonic crystals make the microwave devices possible in micron size [3]. Another benefit of magnonic crystal is that the frequency position and the width of a band gap are tunable by the applied of external magnetic field [2].

2. Principle

Spin waves are excited by interaction between the magnetic moments in a magnetic material and electromagnetic fields. When a large dc magnetic field is applied to a magnetic material, the magnetic moments of material become aligned. Furthermore, when a high-frequency magnetic field is applied by means, for exemple, of microwave excitation, the magnetic moments of body undergo oscillatory motion. In addition, every magnetic material has its natural frequency of resonance, and when a magnetic external field of this frequency is applied, ferromagnetic resonance occurs. When magnetic moments perform uniform precession, there is still a phase shift process which occurs near the ferromagnetic resonance frequency. This phase shift propagates to adjacent magnetic moments, causing a “spin wave” motion. Depending on the strength of coupling between the magnetic moments, there are two limiting types of spin waves. If the wavelength is close to lattice constant of material, then exchange interaction between neighboring spins is prevalent, resulting in exchange spin waves. If the wavelength is larger, then dipole interaction is prevalent, producing magnetostatic waves.

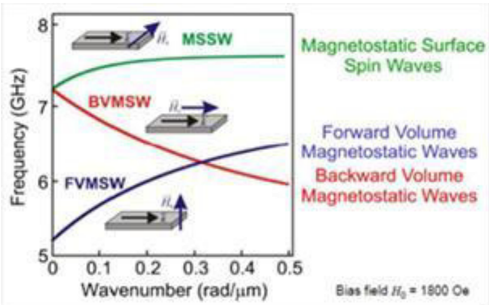

Fig. 1 Magnetostatic waves dispersion curves [2]

There are three propagation modes of magnetostatic waves: magnetostatic forward volume wave (FVMSW) when the magnetic field is applied perpendicular to the film surface, as a magnetostatic back volume wave (BVMSW) when the magnetic field is applied parallel to the film surface and wave propagation is parallel to the field direction, and as a magnetostatic surface wave (MSSW) when wave propagation is perpendicular to the field direction (Fig. 1). In MSSW waves, the energy is concentrated at the surface of the waveguide material and the magnonic band gap can be easily shaped by providing a structure on the surface. For this raison, we used only MSSW waves in this study.

In order to create magnetic periodic inhomogeneities in a spin waveguide, a mechanical structuring of the magnetic materials can be used [5]. A one-dimensional magnonic crystal is obtained when the sample is usually modulated with a periodic array of metallic stripes (gold, copper) deposited or a periodic array of shallow grooves etched on the crystal surface. Both types of these structures are used in our investigation.

3. Experiment

In this investigation, the waveguide for MSSW magnetostatic spin waves consists of monocrystalline YIG film (thickness: 10 µm), grown by isothermal Liquid Phase Epitaxy (LPE) method on a GGG (Gadolinium-Gallium-Garnet) substrate. The in-plane magnetic properties are as follows: saturation magnetization $4\pi Ms$ = 1750 G and the ferromagnetic resonance (FMR) linewidth less than 0.8 Oe. The metal (gold) stripes of periodic structure were fabricated on the YIG film surface using a thermal evaporation technique. The periodic structure consists of 10 stripes of 150 µm, deposited on the YIG film surface (Fig. 2a). The structure of shallow grooves of the same periodicity was built by chemical etched method (Fig. 2b).

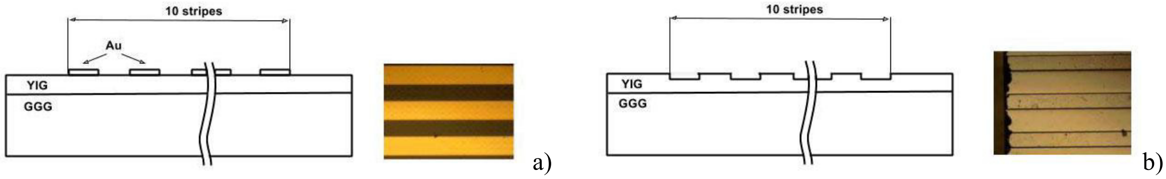

Fig. 2 Magnonic crystal samples: a) with a deposited gold stripe periodic structure b) with an etched groove periodic structure.

The YIG cristal was placed on a transducer (Fig. 3) of microwave signal (microstrip transmission line or two planar microstrip antennas) connected to the Vector Network Analyzer (Agilent VNA 8720A - 130 MHz to 20 GHz) and magnetized perpendicularly to the spin direction of wave propagation by an uniform static in plane dc applied magnetic bias field produced by an electromagnet (with fields as large as 2 kOe). Thus, a high frequency current was passed through by means of the network analyzer used and a high-frequency magnetic field was generated around the microstrip lines allowing the excitation of spin waves. A magnonic stop band was created by a periodic array of metallic stripes or a periodic array of grooves on the crystal surface of the YIG film.

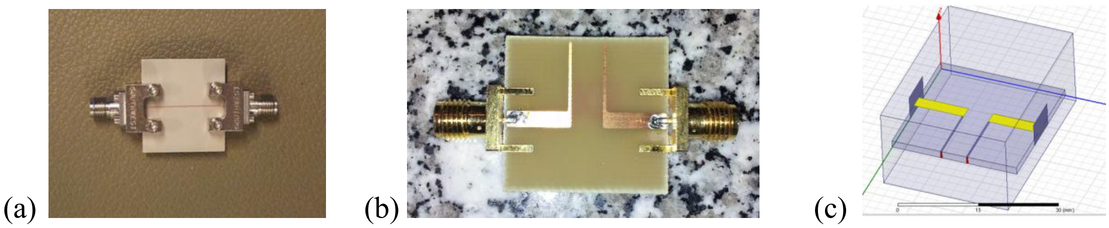

Fig. 3 (a) Microstrip transmission line on TaclamPlus substrate (Taconic) - (b) Microstrip planar antennas on Epoxy FR4 substrate (Rogers) - (c) Microstrip planar antennas simulation by HFSS.

4. Results and discussion

4.1. Microstrip transmission line

The propagation of MSSW waves is limited within a frequency band (from f_{min} to f_{max}) determined on the basis of the applied external bias field and saturation magnetization (Ms) [2]. These frequency limits can be adjusted by the applied magnetic field.

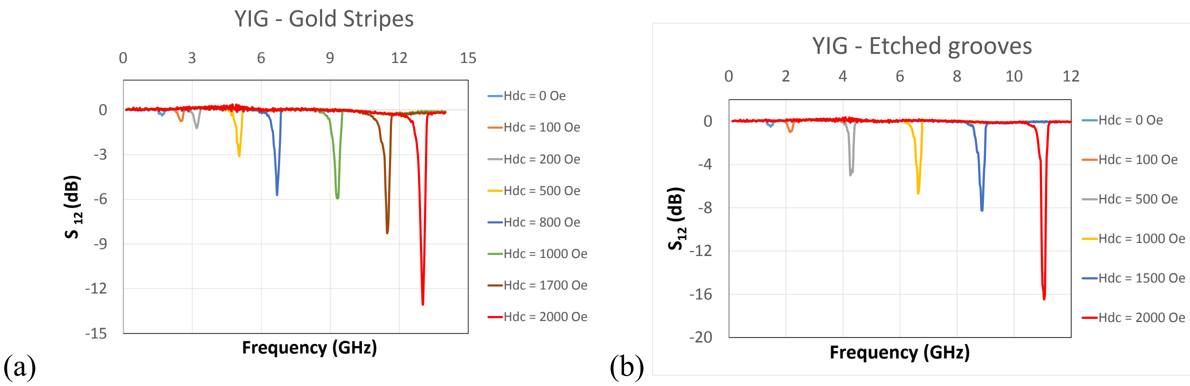

Fig. 4 Variation of the transmission parameter S_{12} of the microstrip transmission line (TaclamPlus substrate) loaded by the YIG magnonic crystals as a function of frequency (0 - 14 GHz), for different bias magnetic fields (0 - 2000 Oe): a) gold stripe periodic structure – b) groove periodic structure.

Figure 4 shows the parameter measurements due to complex transmission coefficients (S_{12}) measured on the microstrip transmission line on YIG magnonic crystals modulated with periodic Au stripes (Fig. 4a) or grooves (Fig. 4b) under the bias field. It shows that the magnonic crystal exhibits a clear, deep, and sharp band gap and a significant shift in the frequency of S_{12} absorption peak. Indeed, the band gap observed in Fig. 4 appears, for exemple, at approximately 3.8 GHz and 3.7 GHz for 500 Oe bias field for the crystal modulated by periodic Au stripes and periodic grooves, respectively. For a field of 400 Oe, this band appears at approximately 3.2 GHz for both cases of modulated structures. Thus, a small change in the bias field causes a wide linear shift in frequency which means that 1 Oe change in the field causes a 6.6 MHz shift in the band gap frequency (for Au stripes).

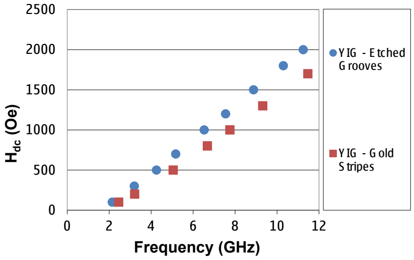

Fig. 5 Variation of peak frequency with increasing bias field.

Figure 5 shows the variation of peak frequency values of gap center with increasing bias field from 0 to 2000 Oe. It shows a good linearity of the curve which is assumed important for sensor applications. The slope of the curve was calculated as 0.15 Oe/MHz (for Au stripes) which reveals that the entire band structure is shifted towards higher frequency with increasing magnetic field. This result suggests that very low magnetic field change could be detected using this magnonic crystal.

4.2. Microstrip antenna line

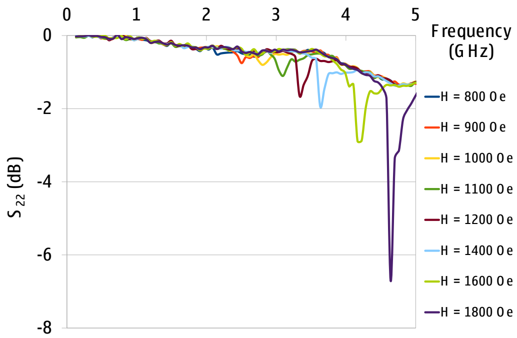

Fig. 6 Reflexion parameter S_{22} of the microstrip antenna structure loaded by a YIG crystal as a function of frequency (150 MHz - 5 GHz) for different bias magnetic fields (0 - 1800 Oe)

To confirm the above results, design of new microstrip antenna structures (Fig. 2.c) is in progress. An electromagnetic simulation software (HFSS) was used to compute the geometric characteristics of the antennas, which were made by a photolithography process on FR4 Epoxy substrate (Fig. 6). These antennas are composed of sections of copper microstrip lines adapted to 50 Ω (width of access lines 2.55 mm, thickness of 1.52 mm substrate) with SMA type connectors 3.5 mm at each ends, connected to two antennas a few tens of microns, with or without ground contacts. The S_{22} reflexion parameter, for an antenna structure loaded by a YIG crystal, was measured between 150 MHz and 5 GHz and a magnetic field range varying from 0 - 1800 Oe. A sharp shift in the frequency of absorption S_{22} peak, induced by variations of the magnetic bias field magnitude can be observed.

This shift in frequency, about 5 MHz/Oe, is similar to the one obtained in transmission parameter S_{12} measurement of the loaded microstrip transmission line.

5. Conclusion

In both types of magnonic crystals tested, the magnonic band gap width decreases with increasing external magnetic field (Fig. 4) [6]. Also, we observed a linear variation of the external magnetic field with the frequency peak values of gap center (S_{12}) with different slopes for the two periodic structures studied (Fig. 5).

It should be noted that optimal excitation of spin waves in the magnonic crystal used is of vital importance, since an efficient transformation of a microwave electromagnetic signal into propagating spin waves with the sub-micrometer wavelength is far not trivial task. This could have a great influence on the sharpness of stop band and thus the detection sensitivity of the magnetic field. To consolidate these results, new microstrip antenna structures (Fig. 2.c) are in progress.

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