Magnonic band-gap meta-materials (one- and two-dimensional magnonic crystals) for magnetic field detection with very high sensitivity

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Abstract

We discuss a magnonic crystal [1-4] which is an artificial magnetic material for the propagation of magnetic waves [5]. A magnonic crystal with one-dimensional or two-dimensional structure can be used as an extremely sensitive three-dimensional magnetic field sensor that is functional at room temperature.

1. Introduction

The highly sensitive measurement of a magnetic field is an important process in various fields of life and medical sciences. A sudden heart attack can be prevented by monitoring the very weak magnetic field–generally of the order of 10^{-7} Oe–originating from the heartbeat6. It is believed that the brain-computer interface can be realized without inserting undesirable electrodes into the brain if the brain information can be extracted by detecting the extremely weak three-dimensional magnetic field (in the 10^{-9} Oe range) originating from the brain activities [7]. The magnetic field measurement is also a significant process in the fields of engineering. For instance, in the case of magnetic data storage, a high density of magnetic recording results in a low magnetic volume which, in turn, results in a weak outgoing magnetic signal [8]. Hence, a highly sensitive sensor is required to accurately detect such a weak magnetic field and read the recorded signals. Giant magneto-resistance (GMR) and tunneling magneto-resistance (TMR) magnetic sensors [9, 10] have played an important role in the development of such highly sensitive sensors.

Among the numerous available magnetic sensors, the SQUID (superconducting quantum interference device) [11, 12] and GMI (giant magneto-impedance) element [13-15] are known to be highly sensitive sensors. SQUID, with a field sensitivity of 10^{-10} Oe, enables us to detect the magnetic field arising from the brain activities, and the GMI element, generally having a detectable field sensitivity of 10^{-8} Oe, enables the detection of the field arising from the heartbeat. Unfortunately, however, these sensors are not sufficiently sophisticated to be applied to technologies such as the brain-computer interface. Owing to a lack of superconducting materials that are functional at room temperature, the operation of the SQUID is currently limited strictly to very low temperatures. Hence, the SQUID is not an appropriate device for simultaneously detecting a localized magnetic field or measuring three-dimensional components of the field. On the other hand, the GMI element equipped with a soft magnetic material is functional at room temperature. It is, hence, more attractive for practical engineering applications, even though its field sensitivity is approximately one-hundredth that of the SQUID. For a proper application of the SQUID, we need to develop a room-temperature superconductor, while for the GMI element, we need to develop a magnetically much softer material. In both cases, these developments are necessary and time consuming.

2. Samples and magnonic band gap

The *magnonic crystal*–an analogy of photonic crystal [16]–can be used to remedy the above situation. A photonic crystal exhibits a photonic band gap in which the propagation of optical (electromagnetic) waves is strictly forbidden. This behavior is because of its artificial periodic structure; the periodic structure acts as a strong reflection wall, owing to Bragg diffraction, whenever the artificial periodicity matches the wavelength of waves. In magnonic crystals, a similar band gap is observed; this band gap corresponds to the propagation of

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magnetic waves, which is supported either by the magnetostatic coupling or exchange coupling of spins, depending on the frequency (wavelength) of the waves. In a relatively lower frequency region, say for a few gigahertz, the effect of exchange coupling reduces and the propagation of the magnetic waves is predominated by magnetostatic coupling. These waves are then termed as magnetostatic waves. On the basis of the relative geometry between the wave propagation direction ***k*** and the bias magnetic field direction $\boldsymbol{H}_o$, magnetostatic waves are classified into three modes. Two volumetric modes, namely, the magnetostatic volume forward wave (MSVFW) and magnetostatic volume backward wave (and MSVBW) modes,[9] appear when $\boldsymbol{k} \perp \boldsymbol{H}_o$ (out-of-plane of ***k***) or $\boldsymbol{k} // \boldsymbol{H}_o$, respectively, while a surface mode, namely, the magnetostatic surface wave (MSSW) mode, appears when $\boldsymbol{k} \perp \boldsymbol{H}_o$ (in-plane of ***k***). In all cases, if the propagation medium (for instance, yttrium iron garnet ($Y_3Fe_5O_{12}$: YIG)) contains some periodicity, a magnonic band gap can be observed for these waves.

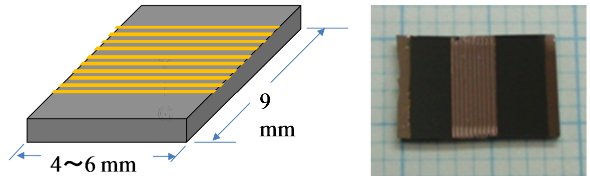

Fig. 1. Fundamental structure of the 1D magnonic crystal.

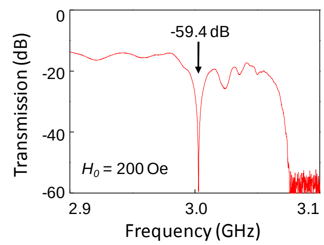

Fig. 2. Magnonic band gap.

Such a periodicity can be easily introduced for MSSW propagation. This is because the wave propagates by confining its energy to the surface of the medium, and the MSSW magnonic band gap is obtained merely by periodically modulating the surface of medium. For such a periodic surface modulation, use of a set of periodic metal stripes directly formed on the surface is a simple way for obtaining a one-dimensional MSSW magnonic crystal, as shown in Fig. 1.

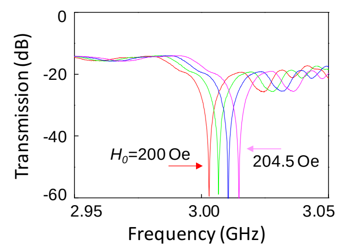

Fig.3 Band gap shift with an *H* field.

The propagation of MSSW is limited within a frequency band ranging from f_{min} to f_{max}; these values are determined on the basis of the applied bias field H_0 and the saturation magnetization of medium M_s [7]. The magnonic band gap can then be designed within such a frequency band between f_{min} and f_{max} by selecting the appropriate periodicity of the metal strips. Under the bias field of H_0 = 200 Oe, the magnonic crystal shown in Fig. 1 exhibited a clear and deep band gap of -59.4 dB at approximately 3.00 GHz; the resonant strength *Q* of this band gap was considerably high (Fig. 2). The deepness of the band gap is closely related to the resonance strength of MSSW at the designated frequency. Hence, in general, a large number of metal stripes results in a high sensitivity for field detection.

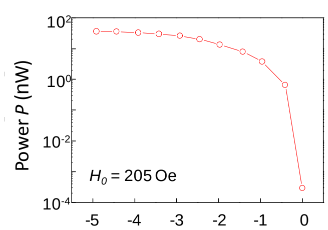

Fig. 4. Field sensitivity.

3. Sensing performance

The frequency of the band gap is very sensitive to the magnetic field applied to the crystal. A small change in the bias field causes a wide linear shift in the frequency; for instance, a 1 Oe change in the field results in a 2.6 MHz shift in the band gap, as shown in Fig. 3. The shift in the magnonic band gap further should ideally result in a similar sort of shift in the MSSW band edge f_{max}. However, this phenomenon is not observed in all cases. This is because such a clear shift in f_{max} is expected only in the case of a low-loss YIG single crystal film, similar to the film we used (ΔH = 0.67 Oe), as such a film exhibits a considerably sharp MSSW band edge. On the contrary, the sharpness of the magnonic band gap is governed by the *Q* factor, which is artificially controlled by adjusting the number of metal strips. Thus, for a high-*Q* magnonic band gap, a similar or superior field-sensitive behaviour could be obtained even with a polycrystalline YIG film.

The large shift in the magnonic band gap results in an extremely large change in the transmission power *P* of MSSW in the vicinity of the band gap. For the sake of comparison with GMI elements, let us evaluate the maximum response sensitivity as a change in output voltage with respect to a unit field: $\left(\Delta\sqrt{P}/\sqrt{P_0}\right)/H_{ex}$. As shown in Fig. 4, the maximum response sensitivity of a magnonic crystal becomes 9336 %/Oe at f = 3.02 GHz and H_0 = 205 Oe. This sensitivity is more than 10 times that of the GMI element (from 377 %/Oe [14] to 600 %/Oe [15]). By selecting an appropriate frequency and bias field and by increasing the *Q* value of the magnonic crystal, a much higher sensitivity can be expected.

4. Conclusion

In this work, the fundamental performance of the one-dimensional magnonic crystal in determining the uni-axial field intensity has been demonstrated. All the data described here were obtained in a normal noisy space without considering any magnetic shielding. Even in such circumstances, the magnonic crystal exhibited its high potential for magnetic field measurement.

At the conference, fundamental performance of a monolithic magnonic crystal with film permanent magnet will also be discussed for realizing two-dimensional propagation of waves and for sensing the magnetic field in the higher dimension.

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