Journal of Magnetism and Magnetic Materials 373 (2015) 30–32

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

# Features of the magnetophotonic crystal spectrum in the vicinity of ferromagnetic resonance

G.O. Kharchenko*, S.I. Tarapov, T.V. Kalmykova

*Institute of Radiophysics and Electronics NAS of Ukraine, 12 Ac. Proskura St., Kharkov 61085, Ukraine*

ARTICLE INFO

*Article history:*
Received 25 November 2013
Received in revised form
7 July 2014
Accepted 11 July 2014
Available online 20 July 2014

*Keywords:*
Ferromagnetic resonance
Magnetophotonic crystal
Spectrum
Wolf–Bragg resonance

ABSTRACT

We theoretically investigate a special phenomenon which reveals in a transmission spectrum of the magnetophotonic crystal. We call it “secondary transmission band” (STB). These bands are located in the main stopband in the vicinity of the ferromagnetic resonance. It is shown that the nature of STB is caused by Wolf–Bragg resonance. The possible methods to control bands amount, their maximum amplitude and their central frequency position are under discussion.



## 1. Introduction

Photonic crystals with magnetic elements (magnetophotonic crystals—MPC) take a special place among the other electrodynamic materials/structures due to the strong dispersion of the crystal components permeability. One of the promising technological implementations and applications of such structures can be their usage as a basis for generation of cheap and compact magnetically controlled passive electronic components (couplers, switches, routers). Here an important issue is the possibility of controlling their spectra [1]. In this connection, the most interesting range of frequencies and magnetic fields is the range of maximum dispersion of the permeability, i.e., the range of ferromagnetic resonance (FMR). Since the value of real part of the permeability increases sharply (by known equations of Landau–Lifshitz) in the vicinity of FMR, this fact can cause very significant, but non-obvious change in the spectrum structure.

In this work, the transmission spectrum of one-dimensional (1D) MPC has been calculated. It was shown that the appearance of a set of “secondary transmission bands” in the spectrum is caused by the sharp increase of frequency dispersion of the real part of ferromagnetic insulator layer permeability.

## 2. Structure of MPC and theoretical approach

The investigated structure is formed by periodically located primary cells which consist of quartz and ferromagnetic insulator layers (Fig. 1).

We have found a theoretical solution to the ($\partial/\partial y \equiv 0$) problem on the plane wave transmission through a structure being studied in a free space. To calculate the transmission spectrum of the MPC, we used one of the widely used methods—the transfer matrix method [2,3]. The permeability of a ferromagnetic insulator layer can be presented as the tensor [4]:

$$\hat{\mu} = \begin{pmatrix} \mu & i\mu_a & 0 \\ -i\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (1)$$

The expressions for the tensor components are determined from the solution of the Landau–Lifshits magnetization motion equation for an infinite ferromagnetic insulator magnetized to saturation and are written as follows:

$$\mu = \frac{\omega_H(\omega_H + \omega_M) - \omega^2}{\omega_H^2 - \omega^2}, \quad (2)$$

$$\mu_a = \frac{\omega\omega_M}{\omega_H^2 - \omega^2}, \quad (3)$$

$$\omega_H = \gamma H - i\alpha\omega, \quad (4)$$

$$\omega_M = \gamma 4\pi M_s, \quad (5)$$

where $\gamma$ is the gyromagnetic electron ratio, $H$ is the external static magnetic field, $M_s$ is the ferromagnet saturation magnetization, $\omega$ is the frequency of the electromagnetic field.

To control the spectral properties of structure under investigation using the magnetic field, it is preferable to use so-called “extraordinary” wave [1,5], which can be excited in the 1D MPC. For this wave [5] the vector of the alternative magnetic field is

* Corresponding author. Tel./fax: +38 57 734 34 63.
*E-mail address:* ganna.kharchenko@gmail.com (G.O. Kharchenko).

http://dx.doi.org/10.1016/j.jmmm.2014.07.011
0304-8853/

perpendicular to the static magnetic field vector $\vec{h} \perp \vec{H}$. Thus, in this case, the effective magnetic permeability takes the well-known form:

$$\mu_{\perp} = \frac{\mu^2 - \mu_a^2}{\mu} \tag{6}$$

## 3. Results and discussion

On the basis of the mathematical model elaborated, we have calculated the transmission spectra of the investigated 1D MPC structure. The calculations were performed for the region of magnetic fields where the FMR frequency lies in the MPC stop-band, specifically, for $H=7$ kOe. The typical transmission spectrum for such a structure is shown in Fig. 2.

It is well known that the spectrum of the periodic structure has a band nature and consists of a set of stopbands (SB) and passbands (PB) [1,3]. However, in this case, the strong frequency dispersion observed in the vicinity of FMR frequency results in a significant change in the spectrum, namely, in the appearance of the set of narrow transmission peaks—“secondary bands”. In particular, in the 1st SB located in the frequency region of 19–29 GHz, to the left of the FMR frequency, a set of narrow peaks arise.

In addition, for the frequencies, which are higher than the ferromagnetic resonance frequency, an additional narrow resonance peak ($f=28.8$ GHz) is observed near the 2nd PB. This peak corresponds to the Wolf–Bragg resonance over the length of the entire structure; i.e., it matches the resonance that arises for the Bloch wave between the first and the last elements of the structure along the *OY* axis. This is confirmed by the numerical analysis of the field distribution at a given frequency (Fig. 3).

The more detailed investigation of the STB region, for the frequencies lower than the ferromagnetic resonance frequency, shows that the narrowing of the ferromagnetic resonance peak up to $\delta H_{1/2} = 1 \times 10^{-4}$ GHz $\approx 3 \times 10^{-2}$ Oe, leads to the situation when these peaks become more pronounced. Moreover, the set of these peaks transforms into the band structure. At the same time, the amount of these bands is also increased (Fig. 4).

A detailed study of the secondary bands form (Fig. 4) allows one to suggest that the nature of secondary bands formation must be the same as that of the main bands, but with the difference that the frequency dispersion of model ferromagnetic insulator permeability is greater and increases with the number of the band. Namely, the source of these bands is Wolf Bragg resonance occurring on the length of each primary cell of the structure (in contrast to the Wolf Bragg resonance arising over the length of the entire structure, Fig. 2).

Then, to estimate the optical length of the MPC primary cell, we can write the following relationship:

$$N \times \frac{\lambda_0^{(N)}}{2} \approx \left[ d_q \sqrt{\varepsilon_q' \mu_q'} + d_f \sqrt{\varepsilon_f' \mu_f'} \right], \tag{7}$$

where $\lambda_0^{(N)} = (c/f_{(N)})$, $N = 1, 2, 3, \ldots$; $d_q$, $\varepsilon_q'$, $\mu_q'$ are the width of quartz layer, real parts of quartz layer permittivity and permeability; $d_f$, $\varepsilon_f'$, $\mu_f'$ are the width of ferromagnetic insulator layer, real parts of ferromagnetic insulator layer permittivity and permeability, respectively. Using formula (7), we calculated a wavelength for each secondary band at the central frequency. Calculations suggested that the integer number ($N$) of half-waves falls within the frequency of each secondary passband in a primary cell of investigation structure. As was expected, the nature of these bands is the Wolf–Bragg resonance occurring in each primary cell in the vicinity of FMR.

It should be noted that this phenomenon could be used effectively to describe the FMR in nanomaterials. It is known that the essential feature of nanoscale magnets is a significant difference in magnetic properties of so-called “bulk” spins (the spins which are surrounded with neighbors on all directions) and so-called “surface” spins (the spins which are located on the surface of magnet and surrounded by neighbors only on one side).

As are shown by many scientists, while size of magnet diminishes to nanoscale the role of so-called “surface” spins grows in contrast to the role of “bulk” spins, and the FMR line broadens.

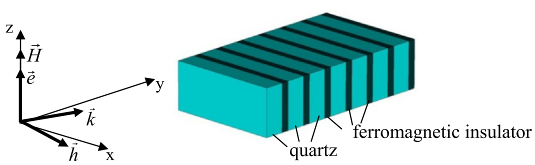


**Fig. 1.** The scheme of structure under investigation—1D MPC.

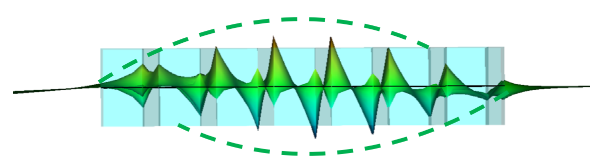

**Fig. 3.** The field distribution of $\vec{e}$-component for the resonance peak at frequency $f=28.8$ GHz.

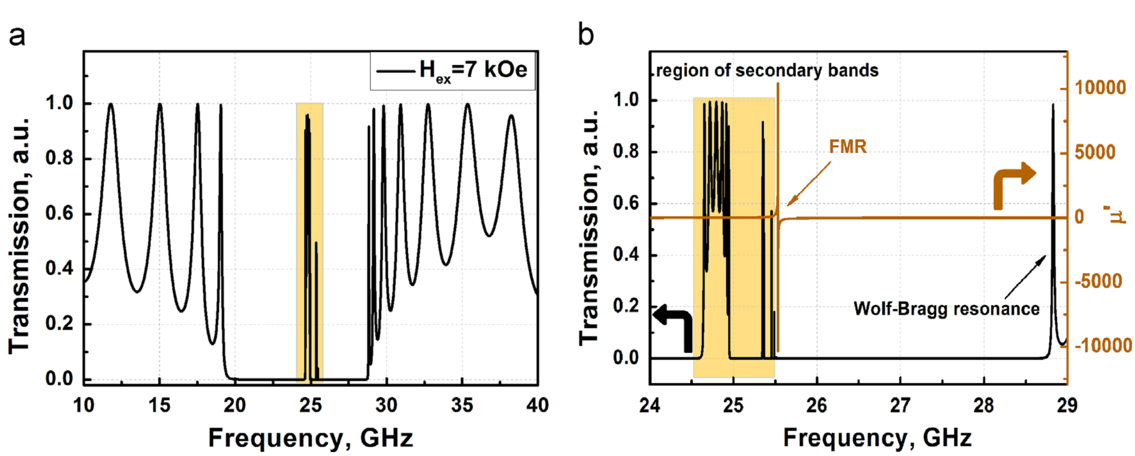


**Fig. 2.** Transmission spectra: (a) MPC at $H=7$ kOe; (b) region of STB—the yellow bar. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

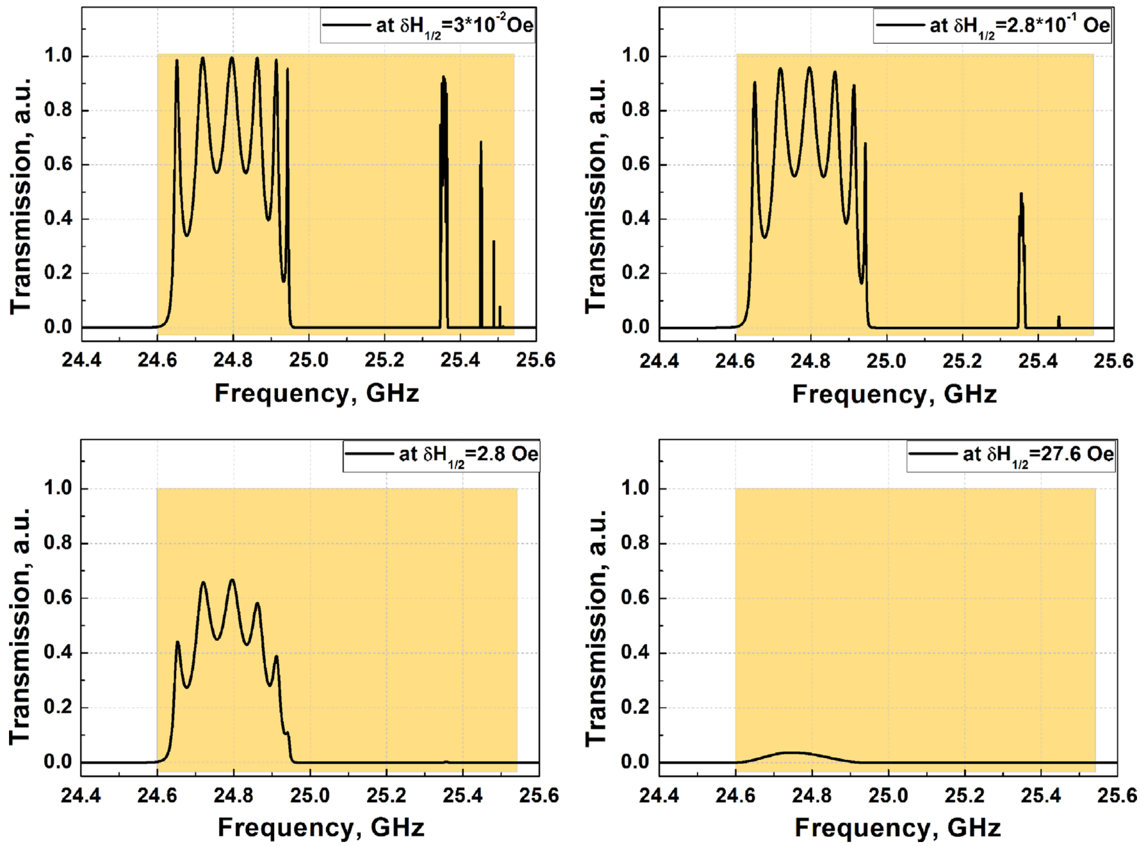


**Fig. 4.** Spectrum evolution with different FMR linewidths in a ferromagnetic insulator layer.

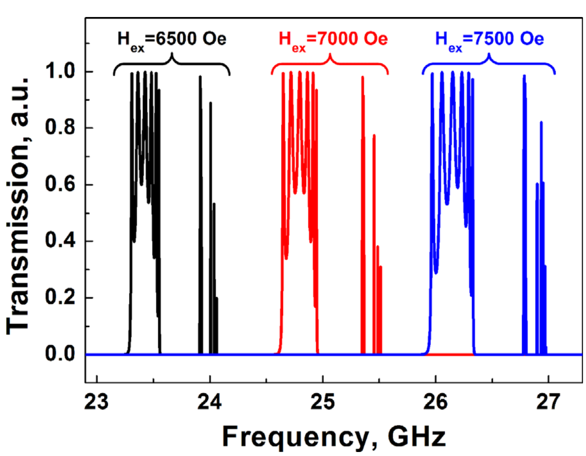


**Fig. 5.** Field dependence of secondary transmission bands.

This allows one to control an amount of STB and their maximum amplitude. On the other hand, this phenomenon provides the possibility of controlling the size of nanoelements of nanoscaled magnet under study.

Another way to tune the secondary transmission bands is the impact of the external static magnetic field on the structure under study. As the magnetically controlled material is the component of the investigated structure, we can see certain changes in the spectrum (Fig. 5). Namely, the growth of the magnetic field leads to the secondary transmission bands shift toward more high frequencies.

Moreover with further increase of the magnetic field the width of the first STB reaches the width of the main passband of the spectrum.

## 4. Conclusions

During the research, the appearance of the set of secondary transmission bands (STB) in the MPC spectrum has been found theoretically in the vicinity of FMR. This is caused by the sharp increase of the real part of ferromagnetic layer permeability. The analysis of the nature of STB was carried out. It has been shown that the origin of secondary bands is caused by the Wolf–Bragg resonance in the primary cell of MPC in the vicinity of FMR. It was shown that the central frequency of each STB is determined by the requirement that the integer number of a half-waves should be packed in the primary cell of the magnetophotonic crystal. It is shown that the central frequency and the width of STB are directly proportional to the external static magnetic field.

## Acknowledgements

The work is partially supported by the Young Scientists Grant no. 10/13 (PION).

## References

[1] S. Chernovtsev, D. Belozorov, S. Tarapov, J. Phys. D: Appl. Phys. 40 (2007) 295.
[2] M. Born, E. Wolf, Principles of Optics, Pergamon Press, New York, 1968.
[3] F.G. Bass, A.A. Bulgakov, A.P. Tetervov, High-frequency Properties of Superlattices Semiconductors (in Russian), Nauka, Moscow (1989) 288.
[4] A.G. Gurevich, G.A. Melkov, Magnetic Resonance in Ferrites and Antiferromagnetics (in Russian), Nauka, Moscow (1973) 591.
[5] A.G. Gurevich, Ferrites at Microwave Frequencies, Heywood, London, 1963.