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Magnetically controllable 1D magnetophotonic crystal in millimetre wavelength band

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Abstract
We analyse the results of experimental and theoretical studies of a 1D magnetophotonic crystal based on the ferrite magnetic periodic multilayered structure. The adequacy of the proposed phenomenological model for description of this crystal in the millimetre waveband is tested experimentally. The possibility to control the spectra of such a structure by variation of the external magnetic field is demonstrated. It is shown that detuning of frequency stop-bands in the spectrum is determined first of all by dispersive properties of the ferrite. The promising applications of such structures as tunable extra high frequency devices are discussed.

1. Introduction

Today electrodynamical structures with spatial periodic refractive index (photonic crystals, PC) are of strong interest for specialists in both theoretical and applied physics [1–8].

In particular, many fundamental problems with promising technological applications are connected with diffraction of extra high frequency (EHF) electromagnetic waves on various periodic structures. The existence of forbidden zones (band-gaps, stop-bands) in the energy spectra of these structures makes it possible to design high-frequency devices and elements [5, 6] such as bandpass filters, antennas, circulators, which are controlled electronically.

The possibility of electronic (in contrast to mechanical) control of such devices in the EHF band (tens to hundreds of gigahertz) is very important. Such control can be realized by changing the fundamental characteristic of the media, its periodical structure and by variation of certain external parameter. One of such parameter, which can be varied effectively, is the magnetic permeability. Therefore magnetic PCs (magnetophotonic crystals, MPC) seem to be very promising for future extra high frequency techniques.

Intensive theoretical and experimental studies [9, 11] have been carried out already in this area with the purpose of developing an effective electronically controlled filter for the high-frequency (HF) band. The corresponding experiments [9, 10] were performed at comparatively low frequencies (no more than 7.8–12.5 GHz) for the periodical structure located in the hollow metal waveguide.

In this paper, we develop a simple theoretical phenomenological model of a 1D ferrite-based magnetophotonic crystal in the higher frequency band (the millimetre waveband). We have demonstrated experimentally the possibility to control the spectral properties of such a crystal with a small external magnetic field. The prospective applications of the 1D ferrite-based MPC as an electronically controlled bandpass filter for the millimetre waveband are discussed.

2. Phenomenological model of 1D magnetophotonic crystal

The structure under consideration is formed by N parallel ferrite layers of thickness d_f, separated by space gaps of thickness d_s (figure 1). The layers are unrestricted in the x- and z-directions. The plane electromagnetic wave with

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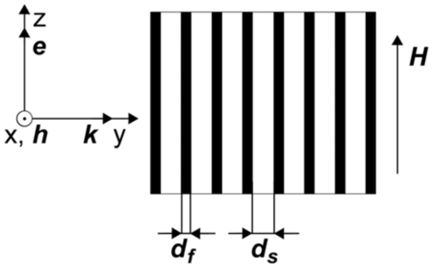

Figure 1. The structure under modelling (***h*** and ***e*** are the magnetic and dielectric components of the ac field, ***H*** is the static magnetic field).

circular frequency ω and wave vector ***k*** falls normally on such a structure. The static magnetic field ***H*** is directed parallel to the layers.

2.1. *Constitutive parameters of ferrite*

Let us consider first the ferrite properties, which are responsible for transmission of electromagnetic wave through the multilayer, neglecting processes of dissipation.

When the external magnetic field equals zero, the properties of a ferrite are isotropic. Its permittivity and permeability are scalars, and $\varepsilon_{\mathrm{f}} \approx 5$–16. The magnetized ferrite media is gyrotropic and its permeability is a tensor of the second rank:

$$\hat{\mu} = \begin{bmatrix} \mu & \mathrm{i} \cdot \mu_a & 0 \\ -\mathrm{i} \cdot \mu_a & \mu & 0 \\ 0 & 0 & \mu_Z \end{bmatrix}. \tag{1}$$

The permittivity in this case is a scalar [12]. It is known that components of this tensor can be represented as solutions of the equation of motion of magnetization [13]. For a saturated ferromagnet we have

$$\mu = \frac{\omega_H(\omega_H + \omega_M) - \omega^2}{\omega_H^2 - \omega^2}, \qquad \mu_a = \frac{\omega_M \cdot \omega}{\omega_H^2 - \omega^2}, \tag{2}$$

where $\omega_H = \gamma H$; $\omega_M = \gamma \cdot 4\pi M_{\mathrm{S}}$; $\omega = 2\pi f$ is the circular frequency of the alternating electromagnetic field, H is the external static magnetic field, M_{S} is the saturation magnetization of a ferromagnet, and γ is the gyromagnetic ratio. The magnitude μ_Z is close to unity and does not depend on the external magnetic field.

However, the behaviour of the spectrum of a magnetophotonic crystal at small external magnetic fields (i.e. at fields of tens to hundreds of Oe, which can be obtained and controlled easily) is of main interest today. Consequently we should use the solution of the equation of motion for the case of non-saturated ferrites. But this problem has not yet been solved rigorously, because we must take into account the motion of domain walls in ferrite. Therefore, below we apply a phenomenological approach and describe the properties of non-saturated ferrites by an empirical expression (for instance [14–16]), which is in good agreement with experiment. In more detail, we used the permeability of absolutely demagnetized ferrite, calculated on the basis of a two-domain model [15]:

$$\mu_{\mathrm{dem}} = \frac{1}{3} + \frac{2}{3}\sqrt{1 - \left(\frac{\gamma \cdot M_{\mathrm{S}}}{\omega}\right)^2}. \tag{3}$$

This relation describes the experiment quite satisfactorily. As well as the indications of many experimental results, we use for diagonal tensor components μ and μ_Z of non-saturated ferrite the expression [16]:

$$\mu = \mu_{\mathrm{dem}} + (1 - \mu_{\mathrm{dem}}) \cdot \left(\frac{M(H)}{M_{\mathrm{S}}}\right)^{3/2}, \tag{4}$$

$$\mu_Z = \mu_{\mathrm{dem}}\left[(1 - M(H)/M_{\mathrm{S}})^{5/2}\right], \tag{5}$$

where μ_{dem} is the permeability of absolutely demagnetized ferrite, defined by (3) and $M(H)$ is the magnitude of the technical magnetization. The dependence $M(H)$ is defined by the experimental way.

Non-diagonal components are defined by the expression (e.g. [12])

$$\mu_a = -4\pi \frac{\gamma \cdot M}{\omega}, \tag{6}$$

obtained by averaging the solutions of magnetization equations of motion over domains.

2.2. *The propagation of the plane wave through the ferrite*

Now using (4)–(6) let us consider the propagation of a plane wave through the ferrite. It is known that Maxwell equations in gyrotropic media [8] have two solutions, which correspond to two normal modes. Each mode has its own propagation constant

$$k_{1,2} = k_0\sqrt{\varepsilon \cdot \mu_{\mathrm{eff1,eff2}}}, \tag{7}$$

where $k_0 = \omega/c$ is the propagation constant in ambient space and c is the velocity of light.

Magnetic properties of the ferrite are different for each mode. These properties are described by μ_{eff1} and μ_{eff2}. The first mode is the 'ordinary mode', for which the vector of magnetic component is directed parallel to the static magnetic field ($\vec{h} \parallel \vec{H}$). This mode has the effective permeability

$$\mu_{\mathrm{eff1}} = \mu_Z. \tag{8}$$

The second one is the 'extraordinary mode' with $\vec{h} \perp \vec{H}$; its effective permeability is

$$\mu_{\mathrm{eff2}} = \frac{\mu^2 - \mu_a^2}{\mu}. \tag{9}$$

Figure 2 shows μ_{eff1} and μ_{eff2} for the high-frequency ferrite (brand 1SCH4).

These dependencies are defined by (4–6) for explicitly non-saturated case ($H < 1000$ Oe) and by (2) for the explicitly saturated case ($H > 1800$ Oe). The dashed line in figure 2 corresponds to the values where the ferrite transforms from non-saturated into saturated state. Here the abovementioned models do not describe the permeability behaviour correctly.

It is easy to see from figure 2 that μ_{eff2} varies with magnetic field more steeply than μ_{eff1}. Therefore, the extraordinary mode is more preferable in order to control the magnetophotonic crystal spectrum.

2.3. Transmission spectra of the multilayered periodical structure

We use the known transfer matrix technique [17] to find the transmission coefficient for the multilayered periodical structure (figure 1). The magnitudes of tangential components of electromagnetic field are linked by the 2 × 2 transfer matrix $\hat{T}$:

$$\begin{bmatrix} e_t(z_2) \\ h_t(z_2) \end{bmatrix} = \hat{T}(z_2,\ z_1)\begin{bmatrix} e_t(z_1) \\ h_t(z_1) \end{bmatrix}. \tag{10}$$

Due to continuity of tangential components on the boundary between layers the transmission matrix is the unit matrix there. The transmission matrix $\hat{M}$ through the whole structure is a multiplication of matrixes for separate layers $\hat{T}_i$:

$$\hat{M} = \prod_{i=1}^{N} \hat{T}_i. \tag{11}$$

The transmission matrix for the ith homogeneous layer is defined by the thickness d_i and the refractive index $n_i = \sqrt{\varepsilon_i \mu_i}$ and has the form

$$\hat{T}_i = \begin{bmatrix} \cos\varphi_i & -\mathrm{i}\dfrac{\sqrt{\mu_i}}{\sqrt{\varepsilon_i}}\sin\varphi_i \\ -\mathrm{i}\dfrac{\sqrt{\varepsilon_i}}{\sqrt{\mu_i}}\sin\varphi_i & \cos\varphi_i \end{bmatrix}, \tag{12}$$

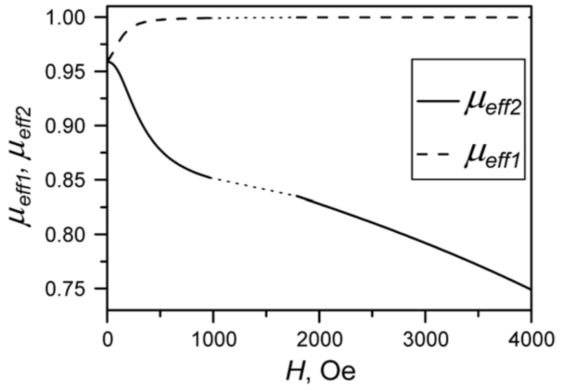

Figure 2. Effective permeability of ferrite (brand 1SCH4, $M_S = 4800$ G) versus the static magnetic field for the ordinary mode ($\vec{h} \| \vec{H}$) and for the extraordinary mode ($\vec{h} \perp \vec{H}$) at $f = 39$ GHz.

where $\varphi_i = k_0 n_i d_i$ is the phase difference between waves before and after the boundary.

The amplitude of transmission coefficient t for the whole structure is connected with the matrix elements by the relation

$$t = \frac{2}{(M_{11} + M_{12}) + (M_{21} + M_{22})}, \tag{13}$$

and the energy-transmission coefficient is

$$T = |t|^2. \tag{14}$$

We calculated the transmission spectrum of the multilayer periodical structure on the grounds of the above-considered model. The structure consists of eight ferrite plates (made of 1SCH4, $M_S = 4800$ G) with thickness $d_f = 1$ mm and space gap thickness $d_s = 2$ mm. The transmission-zones (pass-bands) and stop-zones (stop-bands) are shown in figure 3 at the frequency band 30–85 GHz for the following four cases: (1) $H = 0$; (2)$H = 1$ kOe ($\vec{h} \| \vec{H}$); (3)$H = 1$ kOe ($\vec{h} \perp \vec{H}$); (4)$H = 3.8$ kOe ($\vec{h} \perp \vec{H}$).

It is easy to see that the bands have typical rectangular shapes with some oscillations near edges. It is also important to note that for $\vec{h} \perp \vec{H}$ the stop-band shifts to higher frequencies by $\Delta f \approx 3$ GHz (under changes of the magnetic field 0–3.8 kOe). For $\vec{h} || \vec{H}$ the stop-band shifts to lower frequencies by $\Delta f \approx 0.6$ GHz (under changes of the magnetic field 0–1 kOe). Thereby these graphs demonstrate the possibility of detuning of stop-bands with magnetic field. The steepness of the stop-band edge reaches 0.017 dB MHz^{-1}. It increases with increase in the number of layers. Let us note that the first pass-band shifts more than the second one. That is natural, because the first band is located close to the electron spin resonance (ESR) frequency ($f_{\mathrm{ESR}} = 22.5$ GHz at $H_{\mathrm{ESR}} \approx 6000$ Oe).

3. Experimental

In order to verify the proposed mathematical model, we carried out the experimental study of the periodic structure, consisting of eight ferrite discs (brand 1SCH4, $M_S = 4800$ G) with thickness $d_f = 1 \pm 0.02$ mm and diameter $D_s = 30$ mm. Space gaps are formed by thin rings with thickness $d_s = 2 \pm 0.02$ mm.

The sketch of the experiment is presented in figure 4. The plane wave of the frequency band 27–40 GHz falls on

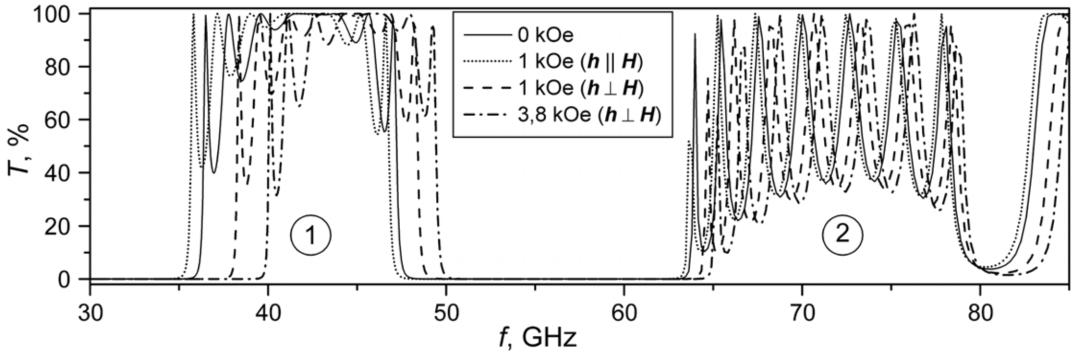

Figure 3. Shift of stop-bands in the transmission spectra of eight-layered 1D MPC for ordinary and extraordinary waves ($d_f = 1$ mm, $d_s = 2$ mm, $M_S = 4800$ G) in a static magnetic field.

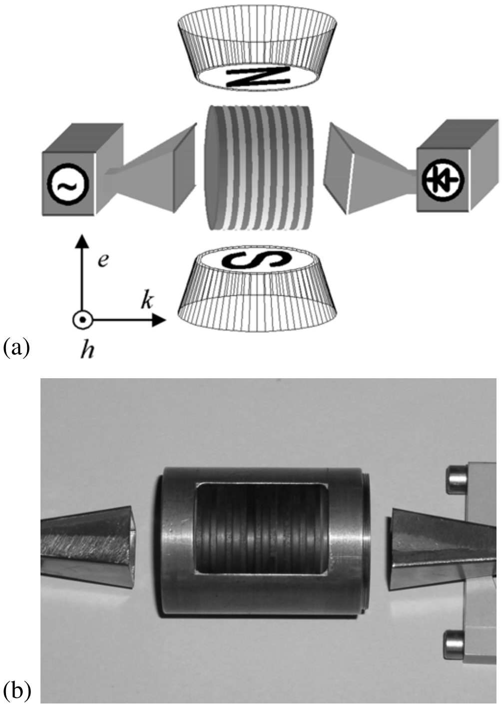

Figure 4. Experimental setup: (*a*) the experimental scheme and (*b*) the photo of the experimental cell.

the multilayer, which is located in the magnetic field between 0 and 4000 Oe. Measurements have been carried out for both $\vec{h} \parallel \vec{H}$ and $\vec{h} \perp \vec{H}$ orientations at room temperature.

In figure 5 a number of experimental and calculated left edges of the first stop-band are presented.

It is easy to see, that the theoretical and experimental curves are in a good agreement in spite of the fact that the theoretical description does not take into account any losses in ferrites. The average error does not exceed $\Delta f = 1.2\%$. Generally the magnetic and dielectric losses should make a noticeable impact on the transmission spectrum. Particularly, the increase in losses should cause the decrease of the maximum of signal in the pass-band and destroy the sharpness of band edges. In fact, in our experiment we can see a manifestation of this influence in the transmission spectra (figure 5) but not in the stop-bands shift (figure 6). This is connected with the following reasons: the stop-bands are produced by the interference of waves reflected from the layers of MPC. Band edges frequencies are defined first of all by the dispersion; that is, by the real parts of both constitutive parameters ($\acute{\varepsilon}$ and $\acute{\mu}$). The module of transmission coefficient is defined primarily by the imaginary part of constitutive parameters. Thus the shift of stop-band of the MPC in an external magnetic field depends primarily on the dispersion parameters and transmission spectra—on the absorption parameters. This fact itself manifests well in our experiments. In particular, from figure 5 one can see that the steepness falls down, and from figure 6 that the shift of the stop-band is satisfactorily described by a lossless model.

We note two points, which are important from the point of view of the applicability.

(a) The noticeable shift of the band edge for the extraordinary mode ($\vec{h} \perp \vec{H}$) takes place in the whole range of applied magnetic fields; it reaches about 3.3 GHz for the field about 3800 Oe. The shift magnitude for the extraordinary mode far exceeds that for the ordinary mode. Therefore just the extraordinary mode (but not the ordinary one) is preferable for the design of electronically controlled devices in the millimetre waveband.

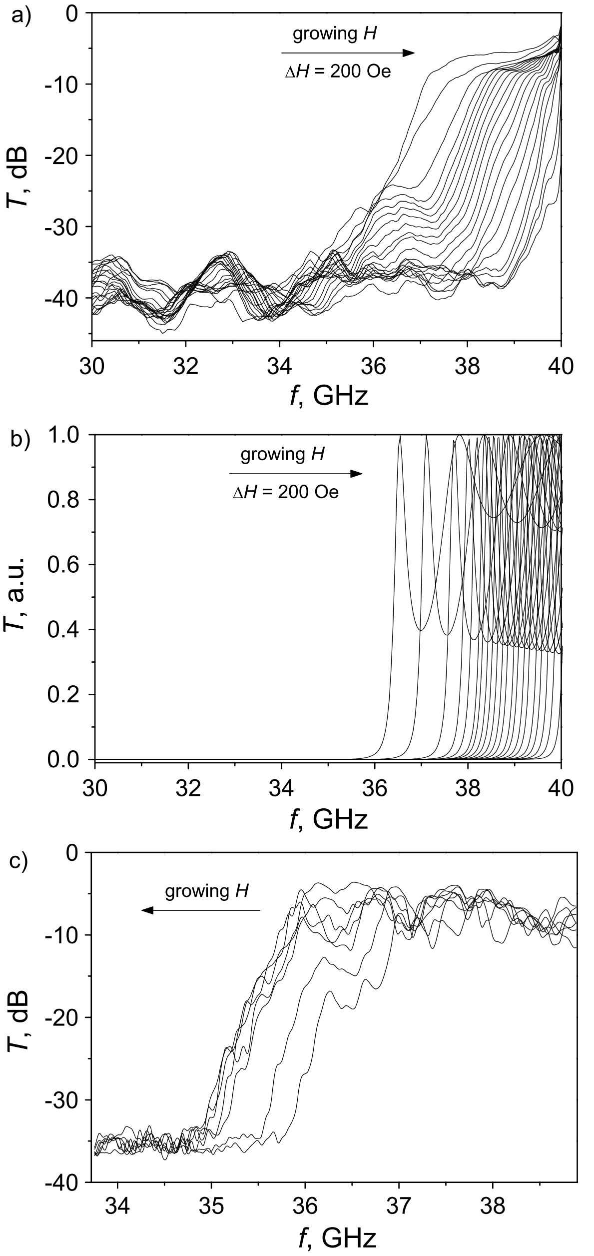

Figure 5. Experimental (*a*) and calculated (*b*) shift of the stop-band edge at various magnitudes of the applied magnetic field for $\vec{h} \perp \vec{H}$ (the field variation step is $\Delta H = 200$ Oe), (*c*) experimental shift of the stop-band edge for $\vec{h} \parallel \vec{H}$ (the curves for $H = 55$, 140, 220, 400, 1500, 2640 and 3820 Oe are presented).

(b) The shifts of stop-band edge for ordinary and extraordinary modes after application of the external magnetic field occur in the opposite directions at the frequency band. This effect can be easily used to realize the electronically controlled separation of waves with mutually orthogonal polarization and to design corresponding EHF devices.

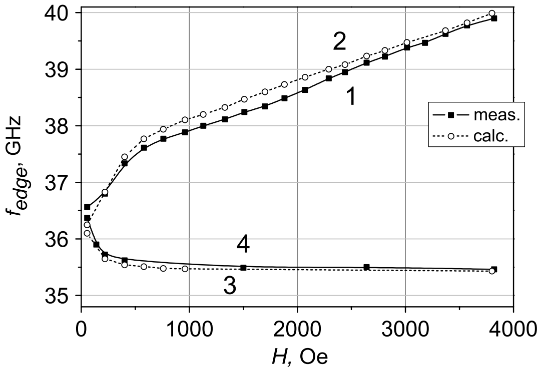

Figure 6. Frequency of the stop-bands edge versus the magnetic field for two waves with the mutually perpendicular polarization: for the ordinary mode (curves 3, 4) and for the extraordinary mode (curves 1, 2).

4. Conclusions

(a) The phenomenological model describing the 1D ferrite-based magnetophotonic crystal of the millimetre waveband is developed. The results of model are in good agreement with experiment.
(b) The possibility to control spectral properties of a 1D ferrite-based magnetophotonic crystal is demonstrated experimentally.
(c) The shifts of stop-band of the spectrum are defined first of all by dispersive properties of the ferrite.
(d) One of the prospective applications of the 1D ferrite-based MPC is an electronically controlled filter in the millimetre waveband.
(e) The distinctions of spectral properties for two waves with orthogonal polarization in ferrite-based 1D MPC allows the use of this structure as an EHF-polarization element.

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