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MAGNETISM AND FERROELECTRICITY

Frequency Control of the Microwave Tamm State

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Abstract—Tunneling of microwave radiation through the surface Tamm state that is generated at the interface between two different periodic structures (photonic crystals) has been studied theoretically and experimentally. The possibility of controlling the transmission frequency of this system with the use of an external magnetic field has been predicted theoretically and confirmed experimentally.

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1. INTRODUCTION

In recent decades, electrodynamics of photonic crystals, including magnetic photonic crystals, has been developed rapidly [1–3]. The fact that the properties of magnetic photonic crystals can be controlled by external magnetic fields greatly enriches the physics of photonic crystals [3–8] and substantially extends the field of their applications [9–13].

Owing to the analogy between periodic electromagnetic structures (photonic crystals) and traditional crystals known in solid state physics, one can expect that the phenomena known from the solid state theory should also be observed in photonic crystals. In particular, the surface Tamm states (the surface solutions that do not contribute to the energy transfer along the surface) in photonic crystals and magnetic photonic crystals have been intensively studied in recent years [10, 11, 14–20].

The existence of the surface states for the magneto-optical systems composed of photonic crystals and magnetic photonic crystals was theoretically considered in our previous works [10, 11]. The properties of these systems depend on the external magnetic field, and, seemingly, this field can be used to control the surface states. However, unfortunately, the effect of the magnetic field on the permeability and permittivity at optical frequencies is extremely weak. For example, the off-diagonal element of the permittivity tensor of magneto-optical materials in a saturation field is no more than a few hundredths of a percent of the diagonal element,[1] whereas a change in the diagonal element in the magnetic field is at least one order of magnitude smaller. This small change in the permittivity makes the magnetic-field control of the Tamm state extremely difficult in practice. In the microwave range, owing to ferromagnetic and ferrimagnetic resonances, the magnetization of the sample leads to a change in the permeability tensor so that a relative change in the permeability can be greater than 100% [21].

In this work, the tunneling of microwave radiation through a surface Tamm state (TS) that appears at the interface between two multilayer periodic systems is considered theoretically and experimentally; each system consists of a finite number of periods and, therefore, can be treated as a bounded photonic crystal. It should be noted that the band structure, the Bloch wave vector, and the Lyapunov factor are determined only by the structure of a unit cell and do not depend of the number of these cells in the sample. The solution inside a one-dimensional photonic crystal is a superposition of two Bloch waves irrespective of the number of unit cells. Therefore, without loss of gener-

[1] Substantially larger values of the off-diagonal element, up to 0.3, are possible near the resonance; however, the high absorption makes these frequencies inapplicable for practical application.

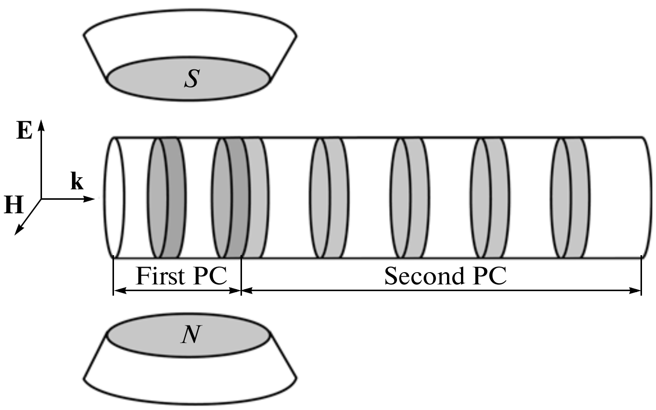

Fig. 1. Schematic diagram of the experiment.

ality, below, we will consider bounded samples containing a small number of periods, like a photonic crystal.

We studied the transmission of an electromagnetic wave through the sample consisting of two photonic crystals (Fig. 1). The first photonic crystal is composed of ferrite layers and vacuum and, hence, is a magnetic photonic crystal, and the second photonic crystal consists of poly(styrene) layers and vacuum. We investigated the dependence of the position of the Tamm transparency peak on the applied magnetizing field. The magnetizing field H_{ex} was applied along the surface of the layers. The incident wave is linearly polarized with its electric field parallel to the magnetizing field (Fig. 1).

2. THE TAMM STATE IN THE MAGNETIC PHOTONIC CRYSTAL

The Tamm state can be formed at the interface between two photonic crystals [11]. The frequency of this state lies simultaneously in the band gaps of both photonic crystals. Therefore, with an accuracy of the periodic Bloch preexponential factor, the electromagnetic field decays exponentially with the distance from the interface. Therefore, this solution is localized near the interface between the two photonic crystals. The existence of this solution appears to be possible owing to the periodic Bloch preexponential factor.[2]

An ideal Tamm state is formed in an infinite system, i.e., at the interface between two semi-infinite photonic crystals. In real experiments, we deal with finite systems, in which the Tamm state results in resonance tunneling of microwave radiation trough the system and appears as a transparency peak in the transmission spectrum at the frequency of the Tamm state.

The frequency of the Tamm state is determined by the equality of the input impedances of the two photonic crystals [11]:

$$Z_1(f) = Z_2(f). \tag{1}$$

It should be noted that these quantities are completely determined by the structure of the unit cell of the photonic crystal but differ from the characteristic impedance averaged over the unit cell. In addition, it should also be noted that the input impedance depends on the direction, so that it is necessary to distinguish the "left" and "right" input impedances. From condition (1), one can find the frequency of the Tamm state f_T.

Since the permeability tensor of the ferrite

$$\mu = \begin{Vmatrix} \mu_1(H_{ex}) & i\chi(H_{ex}) & 0 \\ -i\chi(H_{ex}) & \mu_1(H_{ex}) & 0 \\ 0 & 0 & \mu_2(H_{ex}) \end{Vmatrix}$$

depends on the strength of the magnetizing field H_{ex}, the input impedance of the magnetic photonic crystal (which is composed of the ferrite and vacuum) dependent on the permeability also depends on the external magnetic field H_{ex}. Therefore, we can change the frequency of the Tamm state f_T by changing the magnetizing field H_{ex}.

Unfortunately, purely theoretical investigation of the dependence $f_T(H_{ex})$ is complicated by the necessity of finding the functional dependence of the quantities μ_1, μ_2, and χ on the magnetizing field H_{ex}. The form of the functions $\mu_1(H_{ex})$, $\mu_2(H_{ex})$, and $\chi(H_{ex})$ for real substances is quite different from the model theoretical dependences [21] and depends substantially on the technique for preparing the ferrite. That is why the experimental investigation of $f_T(H_{ex})$ becomes especially important.

3. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

In the experiment, we studied the structure formed by two combined one-dimensional photonic crystals. The first photonic crystal included two periods each consisting of a ferrite layer with the thickness d_F = 1.00 ± 0.03 mm and an air layer with the thickness d_{S1} = 1.00 ± 0.03 mm. The second photonic crystal included five periods consisting of a poly(styrene) layer with the thickness d_P = 1.59 ± 0.03 mm and an air layer with the thickness d_{S2} = 2.00 ± 0.03 mm (Fig. 1). The ferrite and poly(styrene) layers were disks with the

[2] In the absence of this factor, we were unable to simultaneously fulfill the continuity boundary conditions for the tangential components of the electric and magnetic fields. In particular, no solutions are possible at the interface between two layers with a negative permittivity (inside which the coordinate dependence of the electromagnetic field is purely exponential).

diameter $D = 20$ mm and the thickness d_F and d_P, respectively (Fig. 1). The air layers were formed by poly(styrene) rings with the outer diameter D and the thicknesses d_{S1} and d_{S2}.

We used the polycrystalline nickel ferrite NiO Fe_2O_3 (1SCh4) with the saturation magnetization $M_s = 4800$ G, the permittivity $\varepsilon = 11$, and the loss tangent $\tan\Delta_\varepsilon = 8.1 \times 10^{-4}$. The relative permittivity and the loss tangent of poly(styrene) were $\varepsilon = 2.42$ and $\tan\Delta_\varepsilon = 3.0 \times 10^{-3}$, respectively.

The structure assembled from disks and rings was placed in a measuring cell in the form of a hollow ebonite cylinder, which absorbed radiation propagating in radial directions (in order to exclude the excitation of waveguide modes). The structure was fixed inside the cell by an ebonite ring. The measuring cell was firmly mounted in the gap of an electromagnet to exclude the displacement of the magnetic layers due to the magnetic field.

The Agilent N5230A microwave network analyzer was used as a radiation generator and a detector. A waveguide tract was assembled of 7.2 × 3.4 mm hollow rectangular metallic waveguides with horns at the ends of emitting and receiving waveguides.

The constant magnetic field was produced by the electromagnet. The measuring cell with the structure under investigation was placed between the horns in the electromagnet gap. The wave was incident normally to the layer plane of the structure. The constant magnetic field was perpendicular to the magnetic component of the wave. For this field configuration, the so-called extraordinary mode propagated in the ferrite. Teflon lenses used to transform the spherical wave front into the plane front were also located between the horns and the structure. We measured the transmittance in the frequency range 23–40 GHz. The constant field was varied from 0 to 4500 Oe. The accuracy in the measurement of the magnetic field was no worse than 5%. The nonuniformity of the external magnetic field in the volume of the magnetic layers of the structure was no more than 1% and did not significantly affect the observed effects. The bandpass flatness was calibrated before the measurement in the absence of the measuring cell with the structure. The power of the emitted signal was –2 dB with respect to 1 mW.

4. RESULTS AND DISCUSSION

Let us first consider the unmagnetized system of two photonic crystals (with the remanent magnetization of the order of 50 Oe) shown in Fig. 1. The frequency dependence of the transmittance $T(f)$ (Fig. 2, curve *1*) exhibits a transparency peak near 31 GHz. In

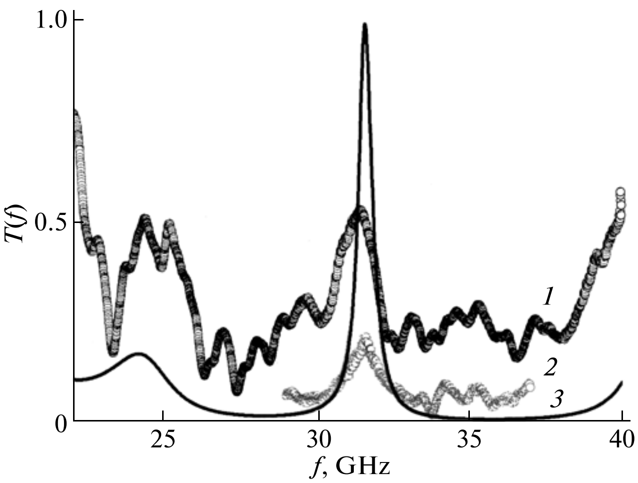

Fig. 2. Frequency dependence of the transmittance $T(f)$ through the systems of the unmagnetized magnetic photonic crystal and the photonic crystal from poly(styrene) and vacuum.

order to show that this is the Tamm resonance (rather than, e.g., the Fabry–Perot resonance), the thickness of each photonic crystal participating in the formation of the Tamm state was increased by one period. In other words, we added the corresponding period on both sides of the system (Fig. 1) (the air/ferrite period was added at the left, and the air/poly(styrene) period was added at the right). Like the frequency dependence of the system under investigation, the frequency dependence of the transmittance $T(f)$ of this reference system (three air/ferrite periods and six air/poly(styrene) periods) exhibits a transparency peak near 31 GHz (Fig. 2, curve *2*). It can be seen that the resonance frequency does not change upon addition of extra periods and, consequently, the resonance is not associated with the thickness of the photonic crystals forming the system, as is the case with the Fabry–Perot resonance.

The theoretical calculation was performed with the use of the T-matrix technique and by ignoring the remanent magnetization as according to the technique described in our previous work [11]. According to the calculation, the Tamm state and the corresponding transparency peak of the system under investigation appear at a frequency of 31 GHz (Fig. 2, curve *3*). Therefore, the observed transparency peak is associated with the formation of the Tamm state at the interface between the photonic crystal and magnetic photonic crystal.

The difference between the calculated and experimental transmittances is most likely due to the finite beam aperture (8 mm), which is comparable to the wavelength. The T-matrix calculation did not take

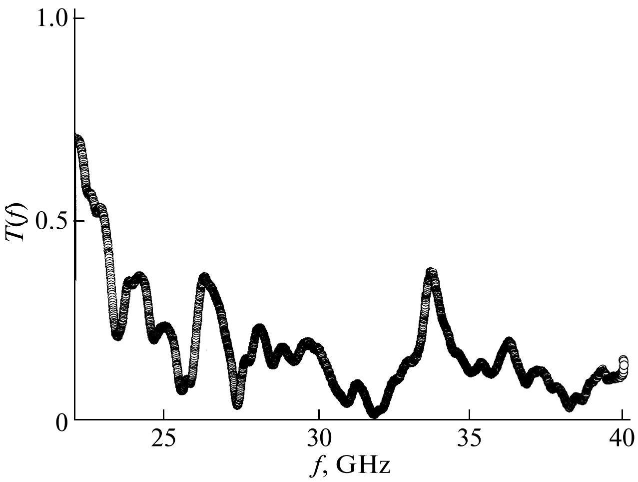

Fig. 3. Frequency dependence of the transmittance $T(f)$ through the system in the field $H_{ex} = 6240$ Oe.

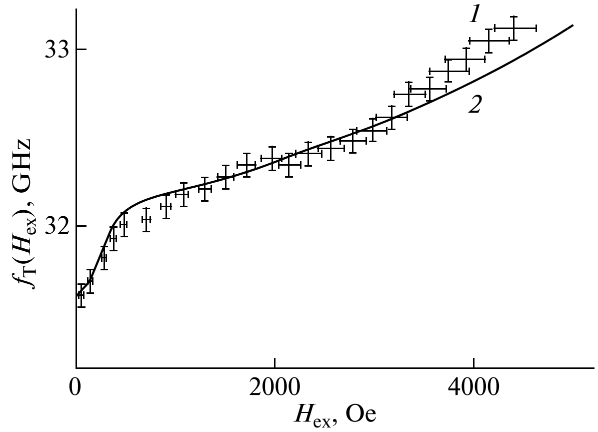

Fig. 4. (*1*) Experimental dependence and (*2*) theoretical evaluation of the dependence of the frequency of the Tamm state f_T on the magnetizing field H_{ex}.

into account the finite aperture of the incident wave. The smallness of the aperture leads to a considerable diffraction divergence and, therefore, to the energy loss upon multiple reflections within the system. The energy loss, in turn, results in a decrease in the Q factor of the resonance and hence in smearing of the transparency peak.

Let us now consider the magnetized sample. At a magnetization of 6240 Oe, the transparency peak previously observed at 31 GHz (Fig. 2) is shifted to 34 GHz (Fig. 3).

To estimate the magnetizing-field dependence $f_T(H_{ex})$ of the frequency of the Tamm transparency peak, we used the known dependence of the permeability tensor μ on f and the magnetization M [22, 23]

$$\mu = \begin{pmatrix} \mu_0 - (1-\mu_0)(M/M_s)^{3/2} & i\gamma M/f & 0 \\ -i\gamma M/f & \mu_0 - (1-\mu_0)(M/M_s)^{3/2} & 0 \\ 0 & 0 & \mu_0^{(1-M/M_s)_0^{5/2}} \end{pmatrix}, \quad (2)$$

where $\mu_0 = \frac{1}{3} + \frac{2}{3}\sqrt{1-(\gamma M_s/f)^2}$ is the permeability of completely demagnetized ferrite (scalar quantity), M_s is the saturation magnetization, and γ is the gyromagnetic ratio. According to the measurements of the permeability of the 1SCh4 ferrite samples (used for preparing our system), the magnetizing-field dependence of the magnetization can be approximated by the expression

$$M = (1 - \sqrt{1-a^{3.01}}/(0.2a + 1.1a^3))/0.0000021 - 5000, \quad (3)$$

where $a = (H_{ex} + 2000)/31600$, the field is measured in Oe, and the magnetization is measured in A/m. This expression agrees well with the experimentally measured permeability of the 1SCh4 ferrite in a magnetic field of up to 1000 Oe, i.e., when the ferrite is not saturated.

Based on dependences (2) and (3) for $H_{ex} < 1000$ Oe and the known dependence for $H_{ex} > 1000$ Oe [21], we theoretically estimated the magnetizing-field dependence of the frequency of the Tamm transparency peak by using the T-matrix method. The results of this calculation are shown in Fig. 4 (curve *2*) and indicate that the frequency of the Tamm state monotonically increases with the magnetization, which becomes noticeable already in relatively low fields, as compared to the saturation field. The experimental dependence (Fig. 4, curve *1*) confirms the theoretical estimate. As can be seen from Fig. 4, the frequency of the Tamm state monotonically increases from 31 to 34 GHz as the magnetizing field H_{ex} increases from 50 to 4500 Oe. Clearly, the theory agrees fairly well with the experiment.

5. CONCLUSIONS

Thus, the possibility of controlling the frequency of the Tamm state with the use of the external magnetic field has been demonstrated experimentally. We succeeded in shifting the frequency of the Tamm transparency peak by 10% by magnetization.

The experimental data agree well with the theoretical prediction. Taking into account that an increase in the aperture of the incident wave (and, correspondingly, in the sample size) should decrease the diffraction losses, which would lead to an increase in the Q factor of the cavity and to the narrowing of the transparency peak, one can expect a potential application of the system under investigation as a magnetically controllable filter.

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