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Strong nonreciprocity of phonon polaritons of an insulator at its boundary with an ideal metal or superconductor in a magnetic field

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Abstract. Surface phonon polaritons in a semi-infinite insulator in a constant magnetic field at the boundary with an ideal metal or a superconductor have been considered. These phonon polaritons are induced by dynamic magnetoelectric interaction, which exists in the presence of a magnetic field. The modes of these surface polaritons appreciably differ in opposite directions of the magnetic field or the propagation of the wave. As a result, polaritons of a given optical or infrared frequency propagate only in one direction with respect to the magnetic field, which is the effect of rectification of surface electromagnetic waves. The inversion of the magnetic field results in 'switching on' or 'switching off' of surface polaritons. The existence of radiant surface polariton modes is predicted.

1. Introduction

Surface polaritons are electromagnetic waves propagating along surfaces or interfaces of media and interacting with their elementary excitations. In the vicinity of the frequency of the elementary excitation, surface polaritons are mixed modes, which are conditioned by the interaction of electromagnetic waves with that elementary excitation. In the UHF region of magnon absorption the polaritons are called magnon polaritons, at optical phonon frequencies they are called phonon polaritons and at plasma frequencies of free electrons the polaritons are plasmon polaritons.

The influence of a magnetic field on magnon and plasmon polaritons is the subject of a wide range of theoretical and experimental studies (see for example [1–8]). Some of these studies are aimed at the investigation of the effects of an external magnetic field on plasmon polaritons in semi-infinite and finite superlattices where semiconducting or metal layers are alternated with insulating ones [3–7]. In these works the permittivity of the insulators is a constant, which is not dependent on frequency.

In works [1] and [2] the interactions of surface plasmon and phonon polaritons in semiconductors in the presence of a magnetic field are considered. The influence of a magnetic field on phonon polaritons appears here only as the result of their interaction with plasmon polaritons, i.e. with free charges.

The influence of a magnetic field on phonon polaritons of an insulator where free charges are absent can be described by the dynamic magnetoelectric energy [9]. This magnetoelectric (ME) energy describes a change of electric polarization in a magnetic field acting on bound

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charges (ions and electrons) of an insulator (see below). The influences of a magnetic field on surface polaritons propagating along an interface of a ferroelectric and a vacuum were discussed recently [10].

In the present work we investigate surface phonon polaritons of a semi-infinite insulator at its boundary with an ideal metal or a superconductor in the presence of a magnetic field parallel to the surface.

It is well known that in an insulator at the boundary with an ideal metal, surface polaritons are impossible [11]. In work [12] the authors found out that in the presence of a constant *electric* field, surface phonon polariton modes appear which are induced by the dynamic magnetoelectric effect. Here we show that in the presence of a constant *magnetic* field, surface polaritons in an insulator also exist and their penetration depth is inversely proportional to the value of the magnetic field. Nonreciprocity, which is typical for elementary excitations in the presence of a magnetic field, turned out to be very strong for the system considered. Phonon polaritons with the given frequency propagate only in one direction with respect to the magnetic field. This is the effect of rectification of surface polaritons. The inversion of a wave vector $\vec{k} \to -\vec{k}$ corresponds to that of the magnetic field.

2. The Hamiltonian and dielectric tensor

Let us consider a uniaxial insulator (Z is an easy axis), though the results obtained are of general significance.

We start from the density of the Hamilton function of optical phonons in external electric and magnetic fields in the form

$$W = \frac{c_1}{2} P_z^2 + \frac{c_2}{2}(P_x^2 + P_y^2) + \frac{\Pi^2}{2\rho} - \vec{e}\vec{P} + \xi \vec{P}\left[\vec{\Pi} \times \vec{H}\right] \tag{1}$$

where $\vec{P}$ is the electric polarization, $\vec{\Pi}$ is the momentum density, $\vec{H} = \vec{H}_0 + \vec{h}$; $\vec{e}$ and $\vec{h}$ are alternating electric and magnetic fields. The uniform external magnetic field $\vec{H}_0$ is imposed in the Y-direction. The last term in (1) corresponds to the dynamic magnetoelectric energy [9]. It is the energy of the interaction of $\vec{P}$ with an effective electric field

$$\vec{E}_{ef} = -(1/c)[\vec{v} \times \vec{H}]$$

produced by the motion of charge e with velocity $\vec{v}$ in the magnetic field (c is the velocity of light). The momentum $\vec{\Pi} = (m/V_0)\vec{v}$; therefore $\xi = V_0/(mc)$ and the constant ρ in the kinetic energy $\Pi^2/(2\rho)$ is $\rho = m/V_0$, where m is the mass of the charge, V_0 being the elementary-cell volume.

In (1) we neglect space dispersion of the electric polarization. Also, we neglect the interaction of surface polaritons with acoustic phonons. Here we will mainly be interested in the IR and optical regions of the spectrum, where the resonance interaction between optical and acoustic phonons is absent.

Generally the electric polarization $\vec{P}$ consists of ion and electron parts. In the IR region of the spectrum the contribution of ions to the magnetoelectric energy is predominant; then m is the reduced mass of an ion–cation pair and $\vec{\Pi}$ is the elementary-cell momentum. In the optical region of the spectrum the electron contribution to the polarization is much greater than the ionic one; m is the electron mass and $\vec{\Pi}$ is the electron momentum. The dynamic magnetoelectric energy (the last term in (1)) is a scalar; thus it is present in the energy of any crystal.

Using (1) we obtain the following Hamilton equations in a linear approximation:

$$\begin{aligned}
\dot{P}_x &= gH_0P_z + \frac{e}{m}\Pi_x & \dot{\Pi}_x &= -\frac{e}{V_0}c_2P_x + gH_0\Pi_z + \frac{e}{V_0}e_x \\
\dot{P}_y &= \frac{e}{m}\Pi_y & \dot{\Pi}_y &= -\frac{e}{V_0}c_2P_y + \frac{e}{V_0}e_y \\
\dot{P}_z &= -gH_0P_x + \frac{e}{m}\Pi_z & \dot{\Pi}_z &= -\frac{e}{V_0}c_1P_z - gH_0\Pi_x + \frac{e}{V_0}e_z \\
g &= \frac{e}{mc}.
\end{aligned} \tag{2}$$

Taking in (2) $\vec{P}$, $\vec{\Pi}$ and $\vec{e}$ proportional to $\exp(-\mathrm{i}\omega t)$, we find the dielectric tensor

$$\begin{aligned}
\varepsilon_1 &= \varepsilon_{xx} = 1 + \frac{4\pi\bar{\omega}_0^2(\omega_e^2 - \omega_H^2 - \omega^2)}{(\omega^2 - \omega_1^2)(\omega^2 - \omega_2^2)} \\
\varepsilon_2 &= \varepsilon_{yy} = 1 + \frac{4\pi\bar{\omega}_0^2}{\omega_0^2 - \omega^2} \\
\varepsilon' &= \mathrm{i}\varepsilon_{xz} = \mathrm{i}(\varepsilon_{zx})^* = \frac{8\pi\omega\omega_H\bar{\omega}_0^2}{(\omega^2 - \omega_1^2)(\omega^2 - \omega_2^2)} \\
\varepsilon &= \varepsilon_{zz} = \frac{(\omega^2 - \Omega_1^2)(\omega^2 - \Omega_2^2)}{(\omega^2 - \omega_1^2)(\omega^2 - \omega_2^2)}.
\end{aligned} \tag{3}$$

Here

$$\begin{aligned}
\omega_{1,2}^2 &= \frac{1}{2}\left[\omega_0^2 + \omega_e^2 + 2\omega_H^2 \mp \sqrt{(\omega_0^2 - \omega_e^2)^2 + 8\omega_H^2(\omega_0^2 + \omega_e^2)}\right] \\
\Omega_{1,2}^2 &= \frac{1}{2}\left[\omega_0^2 + \Omega_e^2 + 2\omega_H^2 \pm \sqrt{(\omega_0^2 - \Omega_e^2)^2 + 8\omega_H^2(\omega_0^2 + \Omega_e^2)}\right] \\
\omega_H &= gH_0 \qquad \bar{\omega}_0^2 = \frac{e^2}{mV_0} \qquad \omega_0 = \bar{\omega}_0\sqrt{c_2} \qquad \omega_e = \bar{\omega}_0\sqrt{c_1} \qquad \Omega_e^2 = \omega_e^2 + 4\pi\bar{\omega}_0^2.
\end{aligned} \tag{4}$$

The frequency ω_e is the excitation frequency of the electric polarization $\vec{P}$ along the easy axis Z, and ω_0 is the excitation frequency of the transverse components of the polarization P_x, P_y in the absence of a magnetic field. For a uniaxial crystal, $\omega_e < \omega_0$.

For ionic excitations (the IR region of spectrum) the gyromagnetic ratio $g \sim 10^{-1}$–10^{-2} A s^2 kg^{-1} m^{-1}; in the optical region of electron excitations $g \sim 10^2$–10^3 A s^2 kg^{-1} m^{-1}. In any case the ratio $\omega_H/\omega_{0,e}$ is small; thus the frequencies $\omega_{1,2}$ and $\Omega_{1,2}$ are approximately equal:

$$\begin{aligned}
\omega_1^2 &\approx \omega_e^2 - \frac{\omega_0^2 + 3\omega_e^2}{\omega_0^2 - \omega_e^2}\omega_H^2 & \Omega_1^2 &\approx \Omega_e^2 + \frac{\omega_0^2 + 3\Omega_e^2}{\Omega_e^2 - \omega_0^2}\omega_H^2 \\
\omega_2^2 &\approx \omega_0^2 + \frac{3\omega_0^2 + \omega_e^2}{\omega_0^2 - \omega_e^2}\omega_H^2 & \Omega_2^2 &\approx \omega_0^2 - \frac{3\omega_0^2 + \Omega_e^2}{\Omega_e^2 - \omega_0^2}\omega_H^2.
\end{aligned} \tag{5}$$

In the absence of a magnetic field the excitation frequencies of P_x and P_y are equal (ω_0) (i.e. there is degeneracy) and the excitation frequency of P_z is ω_e. In the presence of a magnetic field there are two excitation frequencies of P_x and P_z ($\omega_1 \approx \omega_e$ and $\omega_2 \approx \omega_0$) and still one excitation frequency of P_y (ω_0) (see equation (3)). The excitations of P_x and P_z are bound to the modes ω_1, ω_2. In the modes ω_1 and ω_2 the electric polarization precesses around the direction of the magnetic field (see [9]).

The nondiagonal components of the dielectric constant ε_{xz} and ε_{zx} in (3), which indicate the presence of gyrotropy, are proportional to the first power of the magnetic field.

3. Surface phonon polaritons

We consider the phonon polaritons of a semi-infinite (or massive [11]) insulator ($z > 0$) with electric tensor (3) at its boundary with an ideal metal ($z < 0$) (figure 1). Ideal surfaces of the media are assumed. An external constant magnetic field $\vec{H}_0$ is applied along the Y-axis parallel to the interface; polaritons propagate along the X-axis. We solve the Maxwell equations for the insulator with dielectric tensor (3) and take the solution in the absence of damping in the form

$$\vec{e}, \vec{h} \propto \exp\left[\mathrm{i}(k_x x - \omega t) - k_0 z\right] \qquad k_0 > 0 \qquad z > 0. \tag{6}$$

Here k_0^{-1} is the depth of penetration of the field into an insulator.

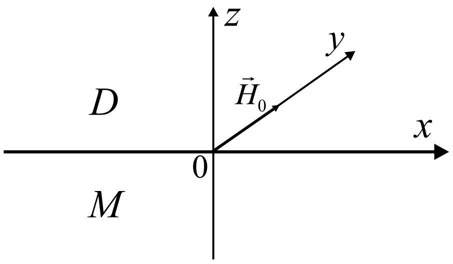

Figure 1. The insulator (D) is in semi-infinite space ($z > 0$); the metal (M) is in space where $z < 0$. The magnetic field $\vec{H}_0$ is along the positive direction of the Y-axis in the contact plane; the wave vector $\vec{k}$ is along the X-axis.

We suppose mechanical strains at the interface to be absent and the boundary conditions at $z = 0$ are the following:

$$b_z = \tilde{b}_z \qquad d_z = \tilde{d}_z \qquad \vec{e}_t = \tilde{\vec{e}}_t = 0 \qquad \vec{h}_t = \tilde{\vec{h}}_t \tag{7}$$

where $\vec{b}$ and $\vec{d}$ are the magnetic and electric induction, $\vec{e}_t$, $\vec{h}_t$ are tangential fields and the letters with tildes refer to an ideal metal. In the case of a superconductor, $\tilde{b}_z = 0$. We also suppose that the magnetic permeability of an insulator $\mu = 1$.

Taking into account (3), (6) and (7), the Maxwell equations can be written as

$$h_y = -\frac{ck_x}{\omega} e_z \qquad h_y = -\frac{\omega}{ck_x} \varepsilon e_z \qquad \left(k_0 - \frac{\omega^2}{c^2}\frac{\varepsilon'}{k_x}\right) e_z = 0. \tag{8}$$

Only e_z and h_y differ from zero in the wave and in this case the depth of their penetration and the dispersion relation are as follows:

$$k_0 = \frac{\omega^2}{c^2}\frac{\varepsilon'(\omega)}{k_x} = \pm\frac{\omega}{c}\frac{\varepsilon'(\omega)}{\sqrt{\varepsilon(\omega)}} \tag{9}$$

$$k_x^2 = \frac{\omega^2}{c^2}\varepsilon(\omega). \tag{10}$$

In our case $b_z = h_z = 0$; therefore, all the results will also hold true when an insulator is in contact with a superconductor.

We see from (9) and (10) that in the case of a contact with an ideal metal the depth of penetration and the dispersion relation of the phonon polaritons of an insulator are determined only by the parameters of the insulator and the external magnetic field. The depth of penetration of the polaritons k_0^{-1} is determined by the value ε', i.e. the ME interaction. In the absence of a magnetic field ($\varepsilon' = 0$), $k_0 = 0$ and surface phonon polaritons do not exist. In a magnetic field, $k_0 \propto H_0$ and bulk polaritons become surface polaritons; thus a constant magnetic field 'pushes out' electromagnetic waves from the insulator. As opposed to the penetration depth, the dispersion relation of surface phonon polaritons (10) depends on the magnetic field weakly.

Taking into account the necessary conditions $k_0 > 0$, $\varepsilon > 0$, expressions (3) and the ratio $\Omega_e > \omega_0$, which is natural for a uniaxial crystal, we obtain the polariton modes, which are shown in figure 2. For ion excitations (the IR region of the spectrum), the gyromagnetic ratio $g > 0$ and figure 2 corresponds to the case $H_0 < 0$. For electron excitations (the optical region), $g < 0$ and figure 2 corresponds to the case $H_0 > 0$. The thick solid curves in figure 2 are modes of surface polaritons ($k_0 > 0$). The dashed curves correspond to 'unphysical' excitations, which increase exponentially inside the insulator ($k_0 < 0$) and, therefore, cannot exist in a massive insulator (regarding the finite thickness of the insulator and the criterion of insulator massiveness, see the conclusions section). The two thick solid curves on the left in figure 2 are modes of polaritons running to the left. Surface polaritons running to the right have one mode (the thick solid curve with $k_x > 0$). The substitution of $-k_x$ for k_x in figure 2 corresponds to the inversion of the magnetic field $H_0 \to -H_0$. In this case, the dashed curves are the modes of surface polaritons and the thick solid curves correspond to 'unphysical' excitations.

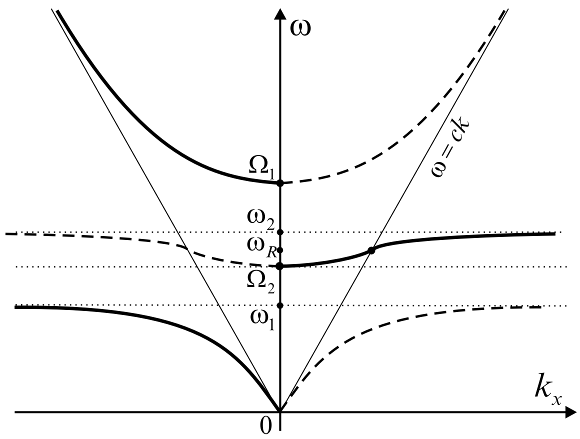

Figure 2. Modes of surface polaritons. Thick solid curves correspond to the case of $\vec{H}_0 \uparrow\uparrow \vec{Y}$ in the optical region and to the case of $\vec{H}_0 \uparrow\downarrow \vec{Y}$ in the IR region. Dashed curves are surface modes for the opposite direction of $\vec{H}_0$.

The ratio of the amplitudes of the electric and magnetic fields in the wave is

$$\left|\frac{e_z}{h_y}\right| = \sqrt{\frac{(\omega^2 - \omega_1^2)(\omega^2 - \omega_2^2)}{(\omega^2 - \Omega_1^2)(\omega^2 - \Omega_2^2)}}. \tag{11}$$

We see from (11) that the magnetic field dominates in excitations near the frequencies ω_1 and ω_2 ($e_z \to 0$). The electric field dominates near the frequencies Ω_1 and Ω_2 ($h_y \to 0$). The vector of electric polarization in the wave precesses around the magnetic field direction. The relation of the components P_x and P_z is

$$\frac{P_x}{P_z} = \frac{\varepsilon_{xz}}{\varepsilon_{zz} - 1} = \mathrm{i}\frac{2\omega\omega_H}{\omega^2 - \omega_0^2 + \omega_H^2}. \tag{12}$$

The frequency range $[\Omega_2, \omega_2]$ for the polaritons running to the right (figure 2) is very small: $\omega_2 - \Omega_2 \sim \omega_H^2/\omega_0$. In the magnetic field $H \sim 10$ T in the optical region of the spectrum, $\omega_H = gH \sim 10^{12}$ rad s^{-1}, $\omega_0 \sim 10^{14}$ rad s^{-1} and $(\omega_2 - \Omega_2)/\omega_2 \sim 10^{-4}$. This mode is a radiant one because of the possibility of a resonance interaction of this mode with the electromagnetic mode $\omega = ck$ (see figure 2). The resonance frequency ω_R is determined from the condition $\varepsilon(\omega) = 1$ (see (10)): $\omega_R^2 = \omega_0^2 - \omega_H^2$. In this mode the relation $|P_x/P_z| \sim \omega_0/\omega_H \gg 1$ holds (see (12)), i.e. the excitation of P_x dominates. This excitation is a weak precession, almost an oscillation of P_x.

The upper mode is also a radiant mode. This mode is almost a transverse one, $|P_z/P_x| \sim \omega/\omega_H \gg 1$, and may be excited by an external electromagnetic wave directly.

When the magnetic field H_0 decreases, the frequency range $[\Omega_2, \omega_2]$ tends to zero, and the magnitude $k_0 \propto \varepsilon' \propto H_0$ also tends to zero, i.e. the depth of penetration k_0^{-1} tends to infinity. In the limit $H_0 = 0$, $k_0 = 0$, the frequencies are $\omega_2 = \Omega_2 = \omega_0$, $\omega_1 = \omega_e$, $\Omega_1 = \Omega_e$ (see equation (5)). Thus ε in equation (3) is $(\Omega_e^2 - \omega^2)/(\omega_e^2 - \omega^2)$ and the dispersion relation (10) turns into the known one for bulk polaritons. 'Unphysical' polariton modes (the dashed curves in figure 2) become real, in the sense that in the absence of a magnetic field there are bulk polaritons with two symmetric excitation branches (the lower and upper curves in figure 2) for which $\omega(-\vec{k}) = \omega(\vec{k})$. Thus, in the absence of a constant magnetic field only bulk polaritons exist in the system considered, which corresponds to the known results [11]. This is also clear from the last equation in (8): at $\varepsilon' = 0$ ($H_0 = 0$), k_0 must be equal to zero, i.e. the depth of penetration $k_0^{-1} = \infty$.

We have from (9) and (3) for the depth of penetration of polaritons into the insulator, k_0^{-1},

$$k_0^{-1} = \frac{c\sqrt{(\Omega_1^2 - \omega^2)(\Omega_2^2 - \omega^2)(\omega_1^2 - \omega^2)(\omega_2^2 - \omega^2)}}{8\pi\omega^2\omega_H\bar{\omega}_0^2}. \qquad (13)$$

Figure 3 shows the frequency dependence $k_0^{-1} = k_0^{-1}(\omega)$. For $\omega > \Omega_1 \approx \Omega_e, \omega \sim \Omega_1$ the penetration depth is of the order of $c\bar{\omega}_0/(\Omega_e\omega_H)$. In the optical region of the spectrum in the field $H \sim 10$ T, $\omega_H \sim 10^{12}$ rad s^{-1}, we obtain $k_0^{-1} \sim 10^{-2}$ cm. Near the frequencies $\omega_{1,2}$, $\Omega_{1,2}$, the penetration depth is even smaller (see figure 3).

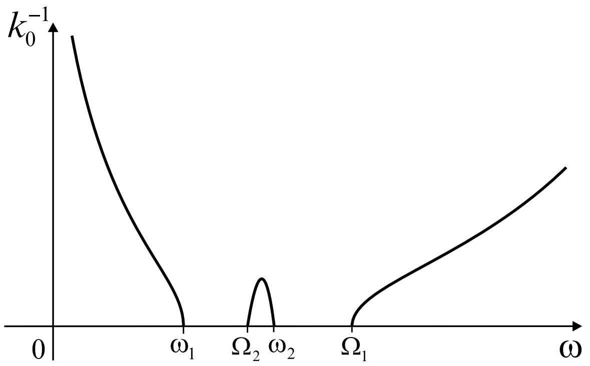

Figure 3. Frequency dependencies of polariton depths of penetration into the insulator.

All results obtained before hold true for the insulator at the boundary with an ideal metal or superconductor where $e_x = 0$. For a real metal, $e_x = \zeta(\omega)h_y \neq 0$, where ζ is the surface impedance of a metal. In this case the equation for k_0 is

$$k_0 + \frac{\omega}{c}\gamma = -\mathrm{i}\frac{\omega}{c}\varepsilon_1\zeta \qquad (14)$$

where $\gamma = \varepsilon'/\sqrt{\varepsilon}$. This means that the results obtained are correct for $|\zeta| \ll |\gamma/\varepsilon_1|$. If

$$\zeta = \frac{(1-\mathrm{i})\omega}{2c}\delta$$

where δ is the depth of penetration of an electromagnetic field into a metal, we obtain the following condition for δ:

$$\delta \ll \delta_0 = \frac{c}{\omega}\left|\frac{\gamma}{\varepsilon_1}\right| \approx \frac{8\pi c\omega_H\bar{\omega}_0^2}{\sqrt{(\Omega_e^2-\omega^2)(\omega_e^2-\omega^2)}\left|\Omega_0^2-\omega^2\right|} \tag{15}$$

where $\Omega_0^2 = \omega_0^2 + 4\pi\bar{\omega}_0^2$. In the optical region, for $\omega > \Omega_e$, $\omega \sim \Omega_e$, $\omega_0 \sim 10^{14}$ rad s^{-1}, $H \sim 10$ T, $\omega_H \sim 10^{12}$ rad s^{-1}, the right-hand side of equation (15), δ_0, is of the order of 10^{-6}–10^{-5} cm. Then the condition $\delta \ll \delta_0$ in the optical region can be realized for example for Cu or Ar, where $\delta \sim 10^{-7}$–10^{-6} cm [11].

In the IR region of the spectrum, the condition (15) could be achieved near the frequencies Ω_e and Ω_0.

4. Conclusions

Thus, in the presence of a constant magnetic field the surface polaritons exist in a semi-infinite insulator, which is in contact with an ideal metal or a superconductor. In this paper we suppose that a surface of contacting media is ideal. We also do not take into account the damping of surface polariton modes, which at IR and optical frequencies is of the order of the phonon damping [13]. The preliminary analysis shows that the damping could destroy the middle branch (see figure 2) due to its extreme narrowness; however, two other modes (the lower and the upper) should be weakly affected by the damping. A semi-infinite insulator can be considered as an insulator whose thickness d is significantly more than the depth of penetration of the surface polaritons, $d \gg k_0^{-1}$. The depth of penetration of the polariton field into the insulator is inversely proportional to the value of the constant magnetic field. Surface modes are strongly nonreciprocal with respect to the propagation direction, $\omega(\vec{k}) \neq \omega(-\vec{k})$. The numbers of modes for waves propagating on the opposite sides are different: two (the upper and the lower branches) and one (the middle branch). The two upper modes are radiant; the lower one is not radiant. The existence of radiant modes indicates the possibility of resonance excitation of these surface polariton modes directly by electromagnetic waves. No modes are close to each other; therefore, excitations with the given frequency propagate only in one direction with respect to the magnetic field. Consequently, we have the possibility of rectifying surface electromagnetic waves in the system considered. The inversion of the magnetic field is equivalent to that of the propagation direction. Thus, the inversion of the magnetic field results in ‘switching on’ or ‘switching off’ of surface polaritons with the given frequency.

For experimental investigations of the predicted effects, the optical region of the spectrum is preferred, where the penetration depth of surface polaritons is less than the one for the IR region. A sufficiently high magnetic field is required to meet the condition $d \gg k_0^{-1}$. Finally, low temperatures are preferred to decrease the influences of the imperfection of surfaces and phonon damping.

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