Thickness dependence of the Casimir force between a magnetodielectric plate and a diamagnetic plate

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This paper examines the repulsive Casimir force between a magnetodielectric plate, with static permeability greater than static permittivity, and a diamagnetic plate. As the thickness of the magnetodielectric plate is decreased, the attractive component of the Casimir force decreases more than the repulsive one. This effect makes the net Casimir force repulsive, and a larger repulsive Casimir force is generated compared to the Casimir force between the plates with infinite thickness.

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I. INTRODUCTION

The effect of magnetic properties on the Casimir force has attracted much attention [1–9]. The significant feature of the Casimir force between a magnetic plate and a dielectric plate is that the direction of the force can be opposite to that between perfectly conductive plates. The sign of the Casimir force between perfectly conductive plates is always attractive independently of the separation. On the other hand, the sign of the Casimir force between a magnetic plate and dielectric plate can change as separation increases.

The repulsive Casimir force has already been observed in liquid [10], and a stable Casimir suspension of dielectric objects may be achieved [11] in the near future. Furthermore, various methods to generate the repulsive Casimir force in a vacuum have been proposed; however, the repulsive Casimir force in a vacuum has not been observed yet. If the repulsive Casimir force is generated in a vacuum, then quantum levitation, which is among the potential applications of the Casimir effect in nanotechnology, may be achieved in a vacuum.

We have shown that the Casimir force between a diamagnetic plate and a magnetodielectric plate can be repulsive for large separations [9]. However, the strength of the repulsive force is very small. To demonstrate the repulsive Casimir force in a vacuum, we need to increase the strength of the force. Thus, the main purpose of this paper is to propose a simple method to increase the repulsive Casimir force. We show that the repulsive Casimir force can be increased by decreasing the thickness of the magnetodielectric plate. In general, the absolute value of the Casimir force between two dielectric plates of finite thickness decreases as their thickness decreases [12]. However, this does not necessarily mean that decreasing the plate thickness will make it difficult to generate the repulsive Casimir force [13] because the direction of the Casimir force is determined by the difference between its attractive and repulsive components. If the attractive component decreases more than the repulsive one as plate thickness decreases, the Casimir force changes from attractive to repulsive. In addition, to demonstrate quantum levitation in a vacuum, it is preferred that the mass of the levitated object be small. Since the mass of the plate per unit area decreases as the plate thickness decreases, the force necessary for levitating it also decreases.

To generate the repulsive Casimir force, we need the permeability of the magnetodielectric plate to be larger than its permittivity. We chose yttrium iron garnet (YIG,$Y_3Fe_5O_{12}$) as the magnetodielectric for the following reasons: First, YIG is a well-known material that exhibits magnetic properties with low permittivity [2]. Second, optical data for YIG have been obtained up to 30 eV [14,15]. Third, ultrathin layers of YIG have been experimentally studied [16]. In addition, the permeability of silicon-doped YIG changes because of the photomagnetic effect. Enz *et al.* observed the change in initial permeability $\mu(0)$ of Si-doped YIG from 160 to 4 in roughly 20 s after illumination [17]. This change allows the Casimir force to be controlled optically.

The essential condition for the repulsive Casimir force between a diamagnetic plate and a magnetodielectric plate is that the permeability of the diamagnetic plate be much less than one for an electromagnetic field at zero frequency, i.e., a dc field. Although the permeability of existing diamagnetic materials is slightly less than one, Wood and Pendry designed a metamaterial having arbitrary effective permeability between zero and one at zero frequency by using a superconductor array, which is referred to as a dc magnetic metamaterial [18]. It has been experimentally confirmed that a superconductor array made of lead has very small permeability [19].

We investigate the dependence on plate thickness of the repulsive Casimir force between a magnetodielectric plate and a diamagnetic plate with infinite thickness using the continuous-medium approximation. The structure of the paper is the following. In Sec. II, we briefly explain the Lifshitz formula at finite temperature. In Sec. III, optical properties of plates are specified. We chose bismuth strontium calcium copper oxide (BSCCO, $Bi_2Sr_2CaCu_2O_{8+\delta}$) [20] as a material of dc magnetic metamaterial, which is well known as a high-T_c superconductor because the thermal Casimir force becomes large as the temperature increases. The dielectric functions of YIG and BSCCO are shown along the imaginary axis considering the static permeability of these plates. In Sec. IV, we show the Casimir force between a YIG plate and BSCCO plate, and discuss the dependence of the Casimir force on the plate thickness. In Sec. V, we present our conclusions and discuss the assumption used in this study.

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II. LIFSHITZ THEORY AT FINITE TEMPERATURE

The Casimir force is caused by boundary alternation of an electromagnetic field and depends sensitively on the shape and optical properties of the boundary. According to the Lifshitz theory [21,22], the Casimir force between plates with infinite thickness per unit area at separation a and temperature T can be expressed by a sum of the following four components:

$$P(a,T) = \sum_{p\in\{\mathrm{TM},\mathrm{TE}\}} P_0^p(a,T) + \sum_{p\in\{\mathrm{TM},\mathrm{TE}\}} P_{l>0}^p(a,T). \quad (1)$$

Here, P_0^{TM} and P_0^{TE} are contributions at zero frequency of the electromagnetic field in the transverse magnetic (TM) and transverse electric (TE) modes, respectively, and $P_{l>0}^{\mathrm{TM}}$ and $P_{l>0}^{\mathrm{TE}}$ are contributions at positive frequencies of the electromagnetic field in TM and TE modes, respectively. The contributions of the electromagnetic field with mode p at zero frequency are given by

$$P_0^p(a,T) = -\frac{k_{\mathrm{B}}T}{2\pi}\int_0^\infty k_\perp^2 dk_\perp \left[\frac{e^{2k_\perp a}}{r_{0,p}^{(1)}(k_\perp) r_{0,p}^{(2)}(k_\perp)} - 1\right]^{-1}, \quad (2)$$

where k_{B} is the Boltzmann constant and $k_\perp$ is the modulus of the wave-vector projection on the plate. We define the optical axis perpendicular to the surface of the plate. In the above equation, the following notations have been introduced:

$$r_{0,\mathrm{TM}}^{(n)}(k_\perp) = \frac{\epsilon^{(n)}(0)k_\perp - \sqrt{k_\perp^2 + \alpha^{(n)}}}{\epsilon^{(n)}(0)k_\perp + \sqrt{k_\perp^2 + \alpha^{(n)}}}, \quad (3)$$

$$r_{0,\mathrm{TE}}^{(n)}(k_\perp) = \frac{\mu^{(n)}(0)k_\perp - \sqrt{k_\perp^2 + \alpha^{(n)}}}{\mu^{(n)}(0)k_\perp + \sqrt{k_\perp^2 + \alpha^{(n)}}}, \quad (4)$$

where n is the index of the plate, and $\epsilon^{(n)}(0)$ and $\mu^{(n)}(0)$ denote permittivity and permeability of the plate, respectively, at zero frequency. The constant α is defined by

$$\alpha^{(n)} = \lim_{\xi\to 0} \epsilon^{(n)}(i\xi)\mu^{(n)}(i\xi)\frac{\xi^2}{c^2}. \quad (5)$$

The contribution to the Casimir force of electromagnetic fields with mode p at positive frequencies is given by

$$P_{l>0}^p(a,T) = -\frac{k_{\mathrm{B}}T}{\pi}\sum_{l=1}^{\infty}\int_0^\infty q_l k_\perp dk_\perp \times \left[\frac{e^{2q_l a}}{r_p^{(1)}(i\xi_l,k_\perp) r_p^{(2)}(i\xi_l,k_\perp)} - 1\right]^{-1}, \quad (6)$$

where $\xi_l = 2\pi k_{\mathrm{B}}Tl/\hbar$ with positive integer l represent the Matsubara frequencies, and $q_l^2 \equiv q_l^2(l,k_\perp) = k_\perp^2 + \xi_l^2/c^2$. The reflection coefficients for positive frequencies are given by

$$r_{\mathrm{TM}}^{(n)}(i\xi_l,k_\perp) = \frac{\epsilon^{(n)}(\xi_l)q_l - k_l^{(n)}}{\epsilon^{(n)}(\xi_l)q_l + k_l^{(n)}}, \quad (7)$$

$$r_{\mathrm{TE}}^{(n)}(i\xi_l,k_\perp) = \frac{\mu^{(n)}(\xi_l)q_l - k_l^{(n)}}{\mu^{(n)}(\xi_l)q_l + k_l^{(n)}}, \quad (8)$$

where $k_l^{(n)} = \sqrt{k_\perp^2 + \epsilon^{(n)}(\xi_l)\mu^{(n)}(\xi_l)\xi_l^2/c^2}$.

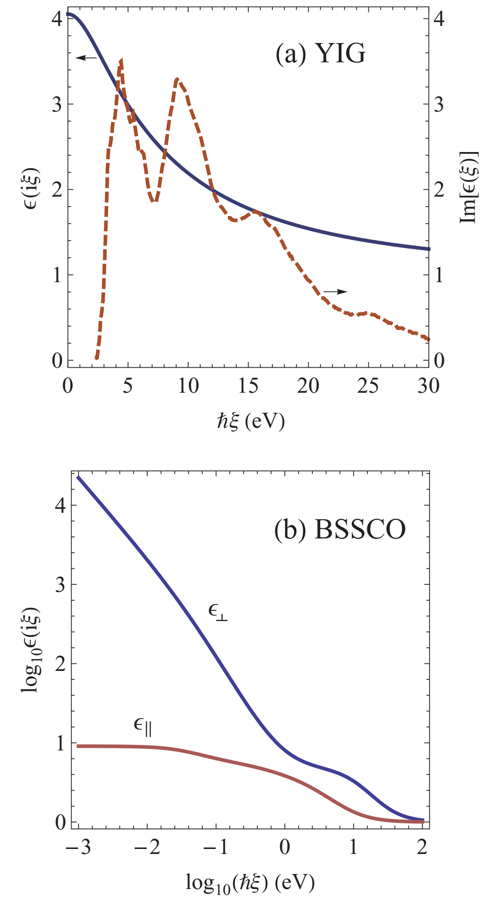

FIG. 1. (Color online) (a) Dielectric permittivity along the imaginary frequency axis (solid line) and imaginary part (dashed line) of permittivity for yttrium iron garnet. (b) Components of dielectric permittivity parallel to the optical axis $\epsilon_\parallel^{(2)}$ and perpendicular to the optical axis $\epsilon_\perp^{(2)}$ along the imaginary frequency axis of permittivity for bismuth strontium calcium copper oxide.

If the thickness of the magnetodielectric plate d is finite, its reflection coefficients are changed as follows:

$$r_p^{(n)} \to r_p^{(n)} \frac{1 - e^{-2k_l^{(n)}d}}{1 - \left(r_p^{(n)}\right)^2 e^{-2k_l^{(n)}d}}. \quad (9)$$

III. OPTICAL PROPERTIES OF PLATES

To consider the dependence of the Casimir force on the thickness of the plate, we need the optical properties of the plates. We specify the optical properties of YIG and BSCCO, which are labeled 1 and 2, respectively. Figure 1(a) shows the permittivity of YIG along the imaginary axis as a function of photon energy $E = \hbar\xi$. The permittivity is calculated using the following Kramers-Kronig relation. In this calculation, we used the experimental results for permittivity obtained by Kahn *et al.* for $2.4 < E \leqslant 5.8$eV [14], and by Kucera *et al.* for $5.8 < E \leqslant 30$eV [15]. We assume that the imaginary part of permittivity for E less than 2.4 eV is zero [23] and is expressed by $(11.6/E)^4$ for $E > 30$ eV [15].

YIG exhibits magnetic resonance at several GHz; however, the resonance frequency is much smaller than the first Matsubara frequency at room temperature, 2.5×10^{14} Hz. Thus, we assume that the permeability along the imaginary axis is zero for nonzero frequencies. Static permeability is susceptible to the temperature, impurity, and diffusants [24]. First, we use $\mu(0) = 160$ as the static permeability of YIG [25]; we later consider the dependence of the Casimir force on static permeability.

The permittivity of BSCCO in the superconductive state has not been sufficiently measured. However, the necessary condition to generate the repulsive Casimir force is that the effective static permeability of the diamagnetic plate must be less than one, and the difference in permittivity between the superconducting and ordinary states does not significantly affect the repulsive Casimir force. Thus, we use the permittivity of BSCCO at room temperature. As shown below, if the thickness of the plate is small, the contribution of the TE mode at zero frequency to the Casimir force is dominant, and is determined by the static permeability and α defined in (5). Since the value of α for BSCCO is zero in both the superconducting and ordinary conducting states, the contribution of the TE mode at zero frequency is determined by the permeability and plate thickness. Furthermore, the permittivity of BSCCO for an electric field polarized perpendicular to the optical axis $\epsilon_\perp$ diverges at zero frequency for both the superconducting and ordinary states. Accordingly, the reflection coefficient for BSCCO at zero frequency becomes one in both cases.

BSCCO is an anisotropic dielectric, and this anisotropy is more important than the difference of permittivity between the superconducting and ordinary conducting states. We use the dielectric function given by Romanowsky and Capasso, who studied the Casimir force acting on BSCCO [20]. The component of permittivity parallel to the optical axis $\epsilon_\parallel^{(1)}$ and the component perpendicular to the optical axis $\epsilon_\perp^{(1)}$ were described in the framework of the oscillator model,

$$\epsilon(i\xi) = 1 + \sum_{j=1}^{K} \frac{g_j}{\omega_j^2 + \xi^2 + \gamma_j \xi}. \tag{10}$$

We took the above parameters (oscillator frequencies ω_j, oscillator strengths g_j, and relaxation parameters γ_j) from Ref. [20]. We chose the optical axis perpendicular to the conducting copper oxide planes. We note that ω_1 in (10) for $\epsilon_\perp(i\xi)$ is zero; $\epsilon_\perp(i\xi)$ diverges at $\xi = 0$. The permittivity of BSCCO along the imaginary axis is shown in Fig. 1(b).

If a dc magnetic metamaterial designed by Wood and Pendry can be made of BSCCO, its effective permeability can be changed from zero and one (see details in Ref. [18]). We assume that the permeability of the diamagnetic plate is zero at zero frequency and one at positive frequency.

For anisotropic dielectric plates, the reflection coefficients defined in (12) are replaced as follows:

$$r_{\mathrm{TM}}^{(n)}(i\xi_l,k_\perp) = \frac{\sqrt{\epsilon_\perp^{(n)}(\xi_l)\epsilon_\parallel^{(n)}(\xi_l)}\,q_l - k_{z,l}^{(n)}}{\sqrt{\epsilon_\perp^{(n)}(\xi_l)\epsilon_\parallel^{(n)}(\xi_l)}\,q_l + k_{z,l}^{(n)}}, \tag{11}$$

$$r_{\mathrm{TE}}^{(n)}(i\xi_l,k_\perp) = \frac{q_l - k_{x,l}^{(n)}}{q_l + k_{x,l}^{(n)}}. \tag{12}$$

Here, $k_{z,l}^{(n)}$ and $k_{x,l}^{(n)}$ are defined as

$$k_{z,l}^{(n)} = \sqrt{k_\perp^2 + \epsilon_\parallel^{(n)}(i\xi)\frac{\xi_l^2}{c^2}}, \tag{13}$$

$$k_{x,l}^{(n)} = \sqrt{k_\perp^2 + \epsilon_\perp^{(n)}(i\xi)\frac{\xi_l^2}{c^2}}. \tag{14}$$

The reflection coefficients for the dc magnetic metamaterial considered here at zero frequency are given by $r_{\mathrm{TM}}^{(2)}(0,k_\perp) = 1$ and $r_{\mathrm{TE}}^{(2)}(0,k_\perp) = -1$.

IV. DEPENDENCE OF THE CASIMIR FORCE ON THE PLATE THICKNESS

The Casimir force between perfectly conductive plates with infinite thickness per unit area is always attractive and is given by

$$P_{\mathrm{c}}(a) = -\frac{\pi^2 \hbar c}{240 a^4}. \tag{15}$$

We consider the ratio of the Casimir force between a YIG plate of thickness d and a superconductive BSCCO plate with infinite thickness to the Casimir force between perfectly conductive plates with infinite thickness. A positive ratio means that the Casimir force between a YIG plate and and BSCCO plate is attractive, while a negative ratio means it is repulsive. Figure 2 shows the ratio of the Casimir force per unit area between the YIG and BSCCO plates for five values of d, that is, 1 μm, 100 nm, 10 nm, 1 nm, and infinity, at 130 K. For any thickness, the Casimir force changes from attractive to repulsive as the separation increases. However, the transition point between the attractive and repulsive forces is different, and it decreases as the thickness decreases. The transition point from the attractive to the repulsive force is 7.8 μm for the Casimir force between plates with infinite thickness. Decreasing the thickness to 1 μm shifts the transition point

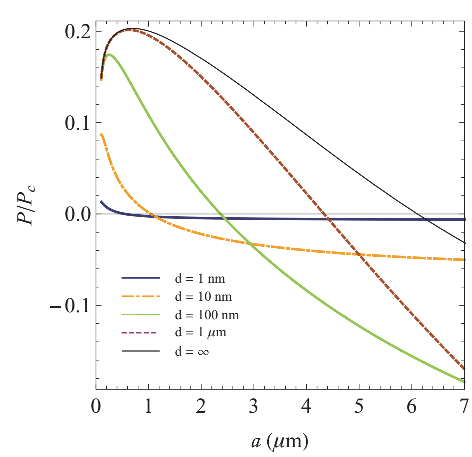

FIG. 2. (Color online) Change with separation of the ratio of the Casimir force between a YIG plate and a BSCCO plate to the Casimir force between perfectly conductive plates for five different values of YIG plate thickness at 130 K. The direction of the Casimir force changes from attractive to repulsive as the separation increases. The separation at which the Casimir force changes from attractive to repulsive decreases as the thickness decreases.

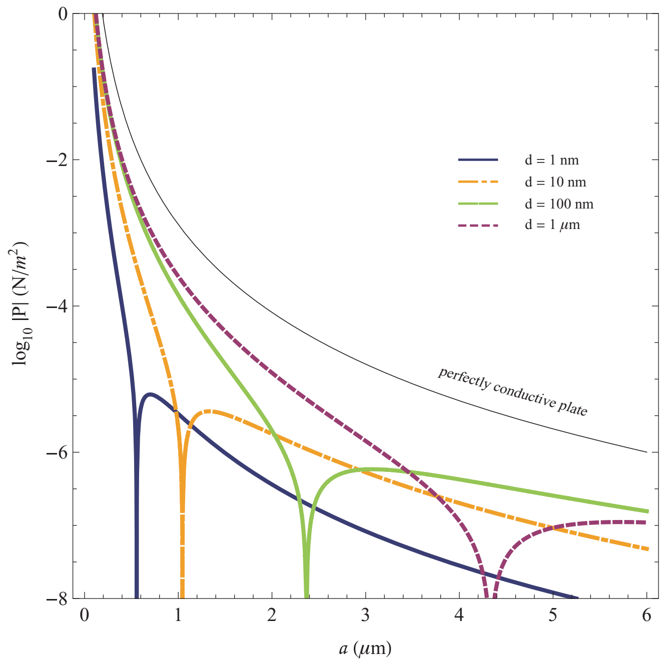

FIG. 3. (Color online) Absolute strength of the Casimir force between a YIG plate and a BSCCO plate on a semilogarithmic scale. The maximum value of the repulsive Casimir force for a fixed thickness of the YIG plate increases as the thickness decreases.

to 4.3 μm. The absolute value of the Casimir force between perfectly conductive plates increases rapidly as the separation decreases. Accordingly, if the ratio is the same, the strength of the Casimir force becomes larger for smaller separations.

Figure 3 shows the absolute value of the Casimir force per unit area between the YIG and BSSCO plates for the same condition. We find that the maximum value of the repulsive force increases as the plate thickness decreases. The Casimir force acting on the YIG plate with 1 μm thickness takes maximum at $a = 5.7$ μm and its strength is 1.11×10^{-7} N/m^2. This value is five times larger than the maximum repulsive Casimir force between plates of infinite thickness. The maximum repulsive Casimir force increases as the thickness decreases, and it is estimated for $d = 100$, 10, and 1 nm as 5.9×10^{-7}, 3.6×10^{-6}, and 6.2×10^{-6} N/m^2, respectively.

Figure 4 shows the dependence of the four contributions in Eq. (1) on plate separation, which are normalized by the Casimir force between perfectly conductive plates $P_c(a)$. Among the four components, only $P_0^{\rm TE}$ contributes to the repulsive force. In contrast, the attractive contribution for large a is mainly determined by the contribution of the electromagnetic field with the TM mode at zero frequency. This contribution is given as

$$P_0^{\rm TM}(a,T) = -\frac{k_B T}{2\pi}\int_0^\infty k_\perp^2 dk_\perp \times \left\{\left[\frac{\epsilon^{(1)}(0)+1}{\epsilon^{(1)}(0)-1}\right]\coth(k_\perp d)e^{2k_\perp a} - 1\right\}^{-1}. \tag{16}$$

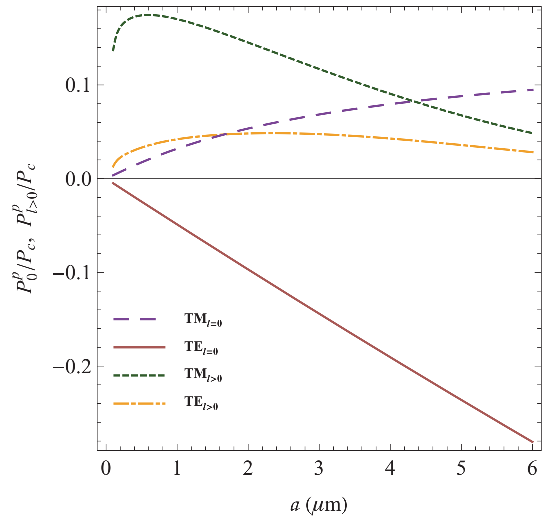

FIG. 4. (Color online) The components of the Casimir force between a YIG plate of thickness 1 μm and a BSCCO plate, which are normalized by the Casimir force between perfectly conductive plates. The component of the TE mode at zero frequency dominantly determines the strength of the Casimir force for larger separations.

For $a \to \infty$ and $d \to 0$, the asymptotic form is given by

$$P_0^{\rm TM}(a,T) \approx -\frac{k_B T}{2\pi}\left(\frac{3}{8}\right)\left[\frac{\epsilon^{(1)}(0)-1}{\epsilon^{(1)}(0)+1}\right]\left(\frac{d}{a^4}\right). \tag{17}$$

Conversely, for $d \to \infty$,

$$P_0^{\rm TM}(a,T) = -\frac{k_B T}{8\pi}{\rm Li}_3\left[\frac{\epsilon^{(1)}(0)-1}{\epsilon^{(1)}(0)+1}\right]\left(\frac{1}{a^3}\right), \tag{18}$$

where ${\rm Li}_n(z)$ is a polylogarithmic function. Thus, to eliminate the attractive contribution for large separations, the plate thickness must be sufficiently smaller than the separation distance.

To explain why the Casimir force changes from attractive to repulsive as the plate thickness decreases for small separations, we must compare the attractive contribution with the repulsive

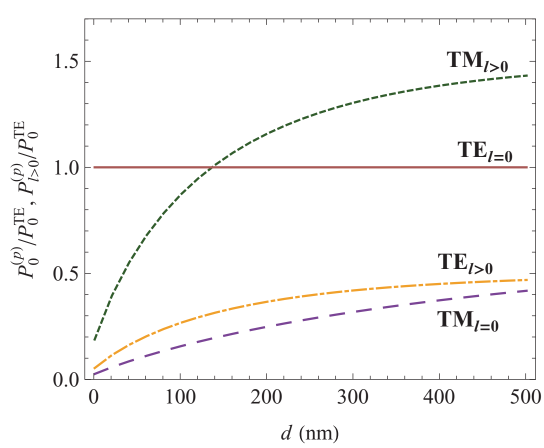

FIG. 5. (Color online) Dependence of the ratio of four contributions: $P_0^{\rm TM}$, $P_0^{\rm TE}$, $P_{l>0}^{\rm TM}$, and $P_{l>0}^{\rm TE}$ to $P_0^{\rm TE}$ at $a = 2$ μm for thickness d. The contribution of the TM mode for positive frequencies becomes smaller compared to that of the TE mode at zero frequency as the plate thickness decreases. The change in the sign of the Casimir force results from this decrease.

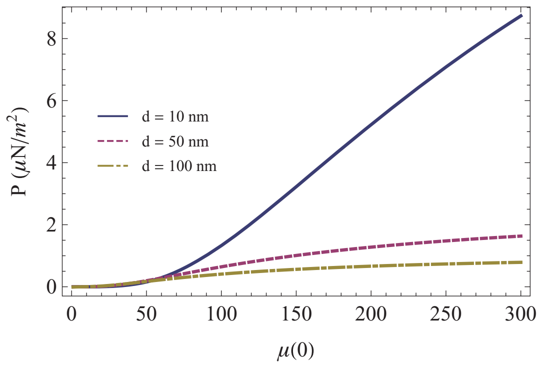

FIG. 6. (Color online) Dependence of the maximum repulsive force on $\mu(0)$ for $d = 100$, 50, and 10 nm. The repulsive Casimir force increases with the permeability of YIG, and this effect is more conspicuous as the plate thickness decreases.

one. Figure 5 shows the absolute value of the ratio of each component to P_0^{TE} at $a = 2\ \mu$m. We find that P_0^{TE} (repulsive contributor) exceeds $P_{l\geqslant 1}^{\mathrm{TM}}$ (main attractive contributor) as the thickness decreases. This reversal can be explained by considering the asymptotic behavior of reflection coefficients for small d as

$$R_p(\xi_l,k_\perp) \approx \frac{2k_l^{(1)} r_p^{(1)}(i\xi_l,k_\perp) r_p^{(2)}(i\xi_l,k_\perp)}{1-\left[r_p^{(1)}(i\xi_l,k_\perp)\right]^2} d. \tag{19}$$

Since the absolute value of the reflection coefficient $|r_p^{(n)}|$ is less than 1, the absolute coefficient of d on the right-hand side of (19) increases as $r_p^{(1)}$ increases. The absolute value of $r_{0,\mathrm{TE}}^{(1)}$ is larger than $r_{\mathrm{TM}}^{(1)}$ in the range that contributes mainly to the integral in (6). Thus, the repulsive contribution, which is the contribution of the TE mode at $\xi = 0$, increases more rapidly as the thickness increases in comparison to other contributors. Then, the net Casimir force becomes repulsive for small values of thickness. The factor $k_l^{(1)}$ in (19) contributes to an increase in R_p as l increases. However, the decrease in $r_p^{(1)}$ as l increases is more significant. Accordingly, the new repulsive force appears not because of the increasing contribution of the repulsive force, but because of the decreasing contribution of the attractive forces.

As mentioned in Sec. III, the permeability of YIG changes depending on many factors, such as temperature and impurity. Thus, we consider dependence of the Casimir force on the permeability of YIG. Figure 6 shows the maximum repulsive Casimir force as a function of the permeability of YIG. The strength of the repulsive Casimir force increases as the permeability of YIG increases and converges to a constant, which depends on the plate thickness. As plate thickness deceases, the repulsive Casimir force saturates at large YIG permeability.

V. CONCLUSION

We have shown that it is possible to change the direction of the Casimir force between a magnetodielectric plate and a diamagnetic plate from attractive to repulsive by decreasing its thickness under several conditions. The first condition is that the magnetodielectric plate should have large permeability and low permittivity, and YIG satisfies both conditions. The second condition is that the permeability of a dc magnetic metamaterial must be less than one. Although the effective permittivity of a dc magnetic metamaterial consisting of a superconducting lead array is much smaller than one, it is not clear whether this effective permeability can be used as the permeability in Lifshitz's formula for the Casimir force between plates. Further studies are needed to verify this assumption. If the Casimir force acting on a dc magnetic metamaterial depends on its static permeability, then the combination of YIG and a dc magnetic metamaterial is a good choice for examining the effect of the Casimir force on the magnetic properties because both the effective permittivity and permeability can be changed together. However, we emphasize that the origin of the repulsive Casimir force between a diamagnetic plate and a superconductor is the Meissner effect. Thus, the structure designed by Wood and Pendry is not an essential condition of the repulsive Casimir force. This is a significant difference compared to the other methods of generating the repulsive Casimir force using a complicated microstructure.

Our method of generating the repulsive Casimir force is closely related to the Casimir force between a magnetodielectric plate and a metallic plate. Geyer *et al.* showed that if the permittivity of a metallic plate obeys the plasma model near zero frequency, the Casimir force can be repulsive for large separations [26]. If the permittivity of the metallic plate diverges near zero frequency in the form $\epsilon(i\xi) = 1 + \omega_p^2/\xi^2$, the value of α defined in (5) is not zero. Accordingly, P_0^{TE} can similarly contribute to the repulsive Casimir force with the results of this study.

Although we have discussed the question of which low-frequency form of the dielectric constant dispersion to use to calculate the Casimir force, the recent measurement of the Casimir force between gold plates by Sushkov *et al.* excludes the plasma model as the correct low-frequency form [27,28]. If the permittivity of metallic plates obeys the Drude model, the value of α is zero; the electromagnetic field of the TE mode at zero frequency does not contribute to the Casimir force. Thus, if the permeability of a plate at a frequency above ξ_1 is zero, one of the plates must possess diamagnetic properties for the electromagnetic field at zero frequency to generate the repulsive Casimir force.

We have found that larger repulsive Casimir forces can be obtained only by decreasing the thickness of a diamagnetic plate within the framework of the continuous-medium approximation. However, this approximation is inappropriate for very small thicknesses. Thus, we need to consider the dependence of the permeability of YIG on the thickness and develop a method of calculating the Casimir force acting on magnetodielectric film beyond the continuous-medium approximation [29].

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