Change in the Casimir force between semiconductive bodies by irradiation

Norio Inui
Graduate School of Engineering, University of Hyogo, 2167, Shosha, Himeji, Hyogo, 671-2280
E-mail: inui@eng.u-hyogo.ac.jp

Abstract. Two topics relevant to the Casimir force (retarded van der Waals force), which is exerted between neutral objects due to the quantum vacuum fluctuations of the electromagnetic field are discussed. First, the enhancement of the Casimir between silicon plates by irradiation is considered. Irradiation generates free carriers inside silicon and it can cause enhancement of the Casimir force between silicon membranes. The temporal behavior of the Casimir force between two parallel silicon membranes after irradiating the surface with UV pulse laser is numerically studied. Based on the Lifshitz theory accounting for thickness of the slabs, the Casimir force as a function of time and the finite size effect of the thickness is calculated. The our experiment in progress to demonstrate the enhancement of the Casimir force by irradiation is also refer. Second, the influence of optical adsorption on the Casimir force acting between a metallic sphere and a semiconductive plate illuminated with Gaussian light beam is considered. The Casimir torque and the lateral Casimir force result form the inhomogeneous photonionization. Taking into account the spatial inhomogeneousness of the plasma frequency in the semiconductive plate, the dependence of the Casimir force on the distance between the optical axis and the center of the sphere is computed within the proximity force approximation.

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1. Introduction

To understand the dynamics of neutral dielectric bodies, the Casimir effect [1, 2, 3] is important, because the Casimir force is dominant force in the long range between dielectrics except gravity. The Casimir effect is widely connected to various scientific fields. In particular, the Casimir force plays an important role in MEMS (Micro Electro Mechanical Systems). For example, Serry et al. argue that the Casimir effect is often an important underlying stiction in MEMS [4].

According to the Lifshitz theory [5, 3], the Casimir force between dielectrics at absolute zero is primarily determined by those dielectric functions. This means that change of the dielectric function causes change of the Casimir force. The conductivity of semiconductor is increased by the generation of the free carriers. The free carriers are generated by illuminating the semiconductor. Thus the Casimir force between the semiconductors increases by illuminating semiconductors with light. Arnold, Hunklinger, and Dransfeld indeed measured this change of the Casimir force between silicon samples [6]. The Casimir force is often cited as manifestations of virtual photons in vacuum. The virtual photons do not affect real photons directly in our macroscopic world, however, the virtual photons may interact with real photons indirectly through interactions with electrons in the semiconductor, and it may lead to a macroscopic effect. From the standpoint of applied physics, this interaction enables to control the Casimir force by light, and we expect to actuate microelectromechanical systems [7] and control non-contact friction by light [8].

In Sec. 2, we consider theoretically the change in the Casimir force between silicon plate after illuminating the surfaces by pulse laser [9]. In Sec. 3, we show that the lateral Casimir force may be generated by illuminating inhomogeneously between a metrical sphere and a semiconductive plate [10]. In Sec. 4 we propose an experiment to demonstrate the above enhancement of the Casimir force.

2. Numerical Study of Enhancement of the Casimir Force between Silicon Membranes by Irradiation with UV Laser

2.1. The Lifshitz theory

We begin to consider the Casimir force between two parallel dielectric plates with the same thickness \(d\). As shown in figure 1, the \(z\) axis is chosen to be perpendicular to the surfaces with a separation \(a\). According to the Lifshitz theory, the Casimir force per unit area between semi-infinite slabs, i.e. \(d=\infty\), with dielectric function \(\epsilon(\omega)\), is given by

\[
F(a) = -\frac{\hbar}{2\pi^2c^3} \int_0^\infty d\xi \int_1^\infty dp \left[ \frac{X_0 e^{-2\xi pa/c}}{1 - X_0 e^{-2\xi pa/c}} + \frac{Y_0 e^{-2\xi pa/c}}{1 - Y_0 e^{-2\xi pa/c}} \right],
\]

where

\[
X_0 = \frac{(s - \epsilon(i\xi)p)^2}{(s + \epsilon(i\xi)p)^2}, \quad Y_0 = \frac{(s - p)^2}{(s + p)^2},
\]
and
\[ s = \sqrt{p^2 - 1 + \epsilon(i\xi)}. \]  

Using the Kramers-Kronig relations [5], the dielectric function with a complex variable, \( \epsilon(i\xi) \) in equation (2) is written as
\[ \epsilon(i\xi) = 1 + \frac{2}{\pi} \int_0^\infty \frac{x\epsilon_2(x)}{x^2 + \xi^2} \, dx, \]  

where \( \epsilon_2(x) \) denotes the imaginary part of dielectric function \( \epsilon(x) \). In the case of finite thickness \( d \), the Lifshitz theory is modified as follows [11, 12]:
\[ F_c(a, d) = \frac{-\hbar}{2\pi^2c^3} \int_0^\infty d\xi \xi^3 \int_1^\infty dp \left[ \frac{X e^{-2\xi p a/c}}{1 - X e^{-2\xi p a/c}} + \frac{Y e^{-2\xi p a/c}}{1 - Y e^{-2\xi p a/c}} \right], \]  

where
\[ X \equiv X_0(\delta - 1)^2 \left(1 - X_0 \delta\right)^2; \quad Y \equiv Y_0(\delta - 1)^2 \left(1 - Y_0 \delta\right)^2, \]  

where \( \delta = e^{-2\xi d/c} \).

The formula (5) is complicated; however it clearly shows that the Casimir force is determined only by three factors: the imaginary part of dielectric function, the thickness, and the gap.

We consider based on the plasma model. Let us assume that the dielectric function is given by
\[ \epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}, \]  

where \( \omega_p \) is the plasma frequency and its typical value corresponding to real metal \( \omega_p \sim 10^{16} \text{s}^{-1} \). To evaluate the right-hand side of equation (5), we use a series expansion method. For high plasma frequency limit: \( \omega_p \gg c/a \), we can express approximately the Casimir force by
\[ F_C(a, d) = F_\infty(a) \sum_{n=0}^\infty \sum_{m=0}^\infty c_{n,m} \alpha^{-n} \beta^m, \]  

Figure 1. Configuration of a pair of silicon membranes.
Table 1. Coefficients of the series expansion of the Casimir force, $c_{n,m}$. Numbers in the first column denotes the exponent of $\beta^{-1}$ and numbers in first row denotes the exponent of $\zeta$. The coefficient $c_{0,0}$ is 1 and $\zeta(k)$ is the Riemann’s zeta function.

| $n \setminus m$ | 0      | 1      | 2      |
|-----------------|--------|--------|--------|
| 1               | $-\frac{15}{3}$ | $-\frac{32}{3}$ | $-\frac{32}{3}$ |
| 2               | 24     | $96 + \frac{4320\zeta(5)}{\pi^4}$ | $192 + \frac{8640\zeta(5)}{\pi^4}$ |
| 3               | $-\frac{640}{7} + \frac{64\pi^2}{147}$ | $-\frac{3840}{7} - \frac{2432\pi^2}{147} - \frac{345600\zeta(5)}{7\pi^4}$ | $-\frac{11520}{7} - \frac{10112\pi^2}{147} - \frac{1382400\zeta(5)}{7\pi^4}$ |

where $\alpha = \omega_p a/c$, $\beta = \exp(-2d/a\alpha)$, and $F_\infty(a)$ denotes the Casimir force between perfectly conducting plates given by

$$F_\infty(a) = -\frac{\pi^2\hbar c}{240a^4}. \quad (9)$$

The coefficients $c_{n,m}$ for $0 \leq n \leq 2$ and $0 \leq m \leq 3$ in Table 1.

In the special case of two perfectly conducting plates separated by vacuum we take $\alpha \to \infty$ and $\beta \to \infty$. Since the dominant factor in the series (8) is the term corresponding to $n = m = 0$, the formula (8) reduces to (9).

In the case of low plasma frequency limit: $\omega_p \ll c/a$, we can obtain an approximate formula

$$F_C(a, d) \sim -\frac{\hbar \omega_p}{16\pi^2 a^3} \int_0^\infty dx \int_0^\infty dy \left[ \frac{1}{X e^{xy} - 1} \right], \quad (10)$$

where

$$X = \left[ \frac{(1 + 2x^2)^2 - \delta}{(1 + 2x^2)(1 - \delta)} \right]^2, \quad (11)$$

and $\delta = e^{-\gamma xy}$. The above double integral is independent of $\omega_p$. Therefore one finds that the Casimir force is proportion to $\omega_p$ for $\omega_p \ll c/a$ and its slope depends on the thickness of plates.

We show the Casimir force $F_C(a, d)$ as function of $\omega_p$. The solid lines in figure 2 are obtained by series expansion (8). One see that solid lines pass on the solid circles which are obtained by integrating the right-hand side of equation (5) numerically for $\omega_p > 10^{15}\text{s}^{-1}$. The dashing lines in figure 2 show the values obtained by equation 10 and it is found that the approximate values are agreed with the values of numerical integral for $\omega_p < 10^{15}\text{s}^{-1}$.

As a result, we see from figure 2 that the Casimir force between plates with a separation $a = 1\mu m$ is almost independent of the plasma frequency above $10^{16}\text{s}^{-1}$ and there is crossover which joins the straight line and almost flat line near $10^{15}\text{s}^{-1}$. The absolute value of the Casimir force between plate with $d = 100\mu m$ is always weaker than that with $d = 1\mu m$ at the same plasma frequency. It, however, implies that if the plasma frequency increase from zero up to $10^{16}\text{s}^{-1}$ by irradiation, the effect of enhancement of the Casimir force between plates with thin thickness is more conspicuous.
Figure 2. Dependence of the Casimir force between dielectric membrane with thickness $d = 100 \text{nm}$ and $d = 1 \mu \text{m}$ on the plasma frequency. Solid lines are obtained by the series expansion method and the slopes of the dashed lines are one.

2.2. Free Carrier density

In the previous section we found that the Casimir force between materials whose dielectric functions are expressed by $1 - \omega_p^2 / \omega^2$ becomes strong as the plasma frequency increases. To calculate the plasma frequency in irradiation, we consider here the temporal and spatial change of the free carrier density in a silicon plate after illuminating on one side of the surface.

We assume that the power of a UV pulse on a plane perpendicular to $z$-axis described in figure 1 is homogeneous and we use a one-dimensional model. Let $n(z,t)$ be the free-carrier density in a silicon plate at position $z$ and time $t$. We set the origin of time the start time of illuminating of a UV pulse and the origin of $z$ the illuminated surface. To calculate the temporal and the spatial distributions of the free carries, we introduce the following diffusion equation with generation and recombination terms:

$$\frac{\partial n(z,t)}{\partial t} = D \frac{\partial^2 n(z,t)}{\partial z^2} + G(z,t) - R(z,t),$$

where $D(17.9 \text{ cm}^2 \text{s}^{-1})$ is the coefficient ambipolar diffusion and $G(z,t)$ and $R(z,t)$ denote the space and the time-dependent rates of the free carrier generation and recombination, respectively. Here the number in the parentheses denotes a value used in the following calculation and it is the same value used in ref. 11.

Let us consider the rate of the free carriers generation. The free carries are generated by receiving the energy from UV laser pulses. The power of light decays exponentially inside silicon and the temporal change of the power at the surface is approximately described by a sine-square. Thus the time dependence of $G(z,t)$ is written as

$$G(z,t) = G_{\max} \sin^2 \left( \frac{\pi t}{2\delta} \right) \exp \left( -\frac{z}{d_{uv}} \right), \quad G_{\max} = \frac{E}{\delta \hbar \nu d A},$$

(13)
where $E(30\mu J)$ is the effective pulse energy, $\delta(1.7\text{ns})$ is the full width half maximum of laser pulse, $h\nu(5.89 \times 10^{-19}\text{J})$ is the photon energy, $d_{uv}(10\text{nm})$ is the absorption depth, $A(2.01\text{mm}^2)$ is the irradiated area.

The recombination term consists of three factors: Auger recombination, radiative recombination, and trap-assisted recombination and it is approximately expressed as

$$R(z, t) = \gamma_3 n^3 + \gamma_2 n^2 + \gamma_1 n,$$

where $\gamma_3(3.8 \times 10^{-31}\text{cm}^6\text{s}^{-1})$ is the Auger recombination coefficient, $\gamma_2(3.3 \times 10^{-15}\text{cm}^3\text{s}^{-1})$ is the radiative recombination coefficient, and $\gamma_1(2.0 \times 10^5\text{s}^{-1})$ is the trap-assisted recombination coefficient.

2.3. Temporal behavior of the dielectric function

According to the Drude theory, the dielectric function of metal with plasma frequency $\omega_p$ is approximately described by

$$\epsilon(\omega) = 1 - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2} \left(1 - \frac{i}{\omega \tau}\right),$$

where $\tau$ denotes collision time. From equation (4) we have,

$$\epsilon(i\xi) = 1 + \frac{\omega_p^2}{\xi(\xi - 1/\tau)}.$$  

Let the number of electrons and holes be $n_e$ and $n_p$ in free carriers, respectively. We assume that the function $\epsilon_{Si}(i\xi)$ of illuminated Si is given by

$$\epsilon_{Si}(i\xi) = 1 + \frac{2}{\pi} \int_0^\infty \frac{x \epsilon''_L(x)}{x^2 + \xi^2} dx + \frac{\omega_{pe}^2}{\xi(\xi - 1/\tau_e)} + \frac{\omega_{pp}^2}{\xi(\xi - 1/\tau_p)},$$

where $\epsilon''_L$ is the imaginary part of the dielectric function of Si before irradiation, $\omega_{pe}$ and $\omega_{pp}$ are the plasma frequencies of an electron and a hole, and $\tau_e$ and $\tau_p$ are the collision time of an electron and a hole. Each plasma frequency is given by the Drude theory:

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e^* \epsilon_0}}; \quad \omega_{pp} = \sqrt{\frac{n_p e^2}{m_p^* \epsilon_0}},$$

where $m_e^*$ and $m_p^*$ denote the effective optical masses of an electron and a hole, $e$ is the elementary charge, and $\epsilon_0$ is the vacuum dielectric constant. For these constants we use the same values presented in Ref. [13]: $m_e^* = 0.2588m_0$, $m_p^* = 0.2063m_0$ ($m_0$ is the electron rest mass), $\tau_e = 1.986 \times 10^{-13}\text{s}$, and $\tau_p = 5.630 \times 10^{-14}\text{s}$.

2.4. Enhancement of the Casimir force between Si plates

We now consider the enhancement of the Casimir force owing to the generation of free carriers. We assume that the inner surface ultraviolet pulse is illuminated. By solving the equation 12, the free carrier density is already obtained as a function of time and the plasma frequencies are also formulized as functions of the free carrier density. We calculate the Casimir force by using the carrier density on the illuminated surface.
To quantify the enhancement of the Casimir force, we calculate a ratio of the Casimir force at time $t$ to that in the absence of illumination. Let a function $R(a, d, t)$ be a ratio of the Casimir force between two silicon membranes with the same thickness $d$ and a separation $a$ at time $t$ to that at $t = 0$. Figure 3 shows the time-dependent evolution of $R(1 \mu m, d, t)$ corresponding $d = 1 \mu m$ and 100 nm. The maximum carrier density on a silicon membrane with a thickness of 100 nm within one pulse is about 5 times as large as that with a thickness of 1$\mu m$, but, the Casimir force between silicon membranes with a thickness of 100 nm is only about 1.25 times larger than that with $d = 1 \mu m$. This difference comes primarily from equation (18), which represents the plasma frequency is proportion to the square of carriers density.

![Figure 3](image-url)

**Figure 3.** Temporal behavior of a ratio of the Casimir force between two irradiated silicon membranes with a separation $a = 1 \mu m$ to that between them in the absence of irradiation.

### 3. Lateral Casimir force induced by inhomogeneous irradiation

In the previous section, we showed that the Casimir force between silicon plates changes by irradiation. This result in the change in the dielectric function of the silicon plates. If the dielectric function changes locally by inhomogeneous irradiation, the Casimir force also may change locally. We consider the Casimir force between a metallic sphere with a radius $R$ and a semiconductor that is illuminated by a Gaussian light beam as shown in figure 4. We denote the center of the sphere and that of the light beam as $C_1$ and $C_2$, respectively.

We begin to consider the Casimir force between a metallic plate and the silicon plate. If the both dielectric function of the metallic sphere and the silicon plate are described using plasma model, and the plasma frequency is much greater than the plasma frequency of the illuminated silicon plate, then the Casimir force for small gap $d$ is approximately given by

$$F(d) = -\frac{\hbar \omega_p}{16\sqrt{2\pi}d^3},$$  \hspace{1cm} (19)

$$\omega_p = \frac{ne^2}{m\epsilon_0}.$$  \hspace{1cm} (20)
\( C_1 \) represents the projection of the center of the sphere to the plate. \( C_2 \) represents the intersection point between the light beam axis and the plate.

where \( n \) denotes the density of carriers and the effective optical mass \( m \) of an electron is 0.25\( m_e \).

To calculate the force between a sphere and a plate, we use proximity force approximation. For a fixed point \( P \), we define \( r_1 \) as the distance between \( P \) and \( C_1 \) and define \( r_2 \) as the distance between \( P \) and \( C_2 \). We should note that the plasma frequency depends the distance \( r_2 \). The plasma frequency at \( P \) is denoted as \( f(r_2) \). The function is determined by the carrier distribution. To determine the carrier distribution, we solve the following diffusion equation:

\[
D \left( \frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} \right) - \gamma n + G_0 e^{-\frac{2(x^2+y^2)}{\sigma^2}} = 0, \tag{21}
\]

where \( D(17.9 \text{cm}^2/\text{s}) \) is the carrier diffusivity, \( \gamma (2 \times 10^5/\text{s}) \) is the recombination coefficient, \( \sigma \sqrt{200 \mu \text{m}} \) is the beam radius and \( G_0(5 \times 10^{25} \text{cm}^{-3}\text{s}^{-1}) \) is the creation rate of free carriers at the origin.

According to the proximity force theory, the vertical force \( F_z \) is given by

\[
F_z(r) = K \int_0^{2\pi} d\theta \int_0^R dr_1 \frac{r_1 f(r_2)}{(R + d_0 - \sqrt{R^2 - r_1^2})^3}, \tag{22}
\]

where \( d_0 \) denotes the minimum distance between the sphere and the plate and \( K = -\hbar/(16\sqrt{2}\pi) \). The distance \( r_2 \) is expressed by \( \sqrt{r^2 + r_1^2 - 2rr_1 \cos \theta} \) using the cosine theorem. Figure 5 shows the absolute value of Casimir force \( F_z(r) \) for \( R=1\text{mm} \) and \( d_0 = 100\text{nm} \) and the differential coefficient of \( F_z(r) \) with respect to \( r \). In this calculation, we suppose that the plasma frequency is determined locally from the carrier density shown in figure 4 by using equation 20. We find that the magnitude of the force changes gently compared with the light intensity profile with the Gaussian beam radius \( \sigma \approx 141 \mu \text{m} \). The first reason why the function \( F_z(r) \) is broad is that the free carriers
diffuses easily beyond the beam radius. The second reason is that the plasma frequency is proportional to not the carrier density, but the square root of the carrier density.

\[ F_z(r) \]

Figure 5. Dependence of the vertical Casimir force acting on a sphere to an illuminated Si plate on the distance between the center of the sphere and the center of the light beam with \( \sigma = 100\sqrt{2}\mu m \). The dashed line shows the differential coefficient of \( F_z(r) \) with respect to \( r \).

Let us calculate the lateral force \( F_r(r) \) form the Casimir energy. Since we can not obtain the Casimir energy between the sphere and the plate exactly, we assume that the approximate energy density per unit area at the position \((r, r_1)\) is given by

\[
 u(r, r_1, \theta) = \int_{d(r)}^\infty F(z)dz,
\]

\[
 = -\frac{1}{2} \frac{f(r_2)}{(R + d_0 - \sqrt{R^2 - r_1^2})^2}.
\]

Then the total Casimir energy \( U(r) \) is defined by \( \int_0^R \int_0^{2\pi} u(r, r_1, \theta)r_1 dr_1 d\theta \), and the lateral force is defined by \( F_r(r) \equiv -\frac{\partial U(r)}{\partial r} \). Figure. 6 shows the magnitude of the lateral Casimir force with 10nm separation. This force acts toward the center of the beam. Similarly with the torque, the magnitude of the lateral force takes the maximum near a circle with the beam radius. The lateral force is much weaker than the vertical force. When the beam radius \( \sigma \) is increased from \( 100\sqrt{2}\mu m \) to \( 400\sqrt{2}\mu m \), the maximum point of the lateral Casimir force shifts outside from the center of the light beam and the maximum value decreases. The lateral Casimir force involves the unbalanced the Casimir energy between the illuminated area and the dark area. Therefore the increment of the illuminated area does not necessarily means the increment of the lateral Casimir force.

4. Proposal for an experiment to demonstrate the enhancement of the Casimir force by irradiation

The Casimir force between a metallic plate and a metallic plate is measured precisely with the use of a torsional pendulum[14], an atomic force microscope(AFM) [15], and
Figure 6. Dependence of the lateral Casimir force acting on a sphere on the distance between the center of the sphere and the center of the light beam.

MEMS technology[7]. The measurement of the Casimir force between silicon bodies is much difficult in compare with that between metallic bodies. Because the magnitude of the Casimir force between silicon bodies is often smaller than that between metallic bodies. The Casimir force between a plate and a sphere is proportional to the radius of the sphere. However, if the Casimir force is determined from the displacement of the sphere, the smaller sphere is suitable to the measurement. Because the response of the heavy sphere to the change of the Casimir force is slow, and the isolation from the source of vibrations with low frequency nose is difficult. As a consequence, the desirable choice is the combination of a cantilever with a small spring constant and a large sphere. There are many commercial cantilevers with a small spring constant for AFM, however, they are usually too small. For this reason, we design a cantilever for the measurement of the Casimir force as shown in figure.7(a).

Figure 7. (a) Dimensions of the cantilever for the measurement of the Casimir force, in which the unit is defined as 1 µm. (b) Scanning electron microscope image

A 1mm square silicon plate with 4mm thickness is connected to a base by two beams with 30µm width and 300µm length. The spring constant and the first eigenfrequency are roughly estimated as 0.1N/m and 970Hz. This cantilever can be made of a SOI(Silicon on Insulator) wafer using photolithography (see figure 8 and figure 7(b)).
Figure 8. Illustration of the production process of the cantilever.

The experimental scheme is straightforward as shown in figure 9. The displacement of the cantilever is measured by a laser interferometer. If the power of the laser is strong enough to excite electrons in the cantilever, this laser interferometer can play a role of a pumping laser, too. Although it is better to illuminate the silicon surface facing the metallic surface in order to increase the carrier density, the excess carriers can move inside the cantilever even if the opposite side is illuminated. There are several points that must be settled in the actual measurement. First, we have to consider the thermal effect. The displacement caused by thermal energy is much larger than the displacement caused by the enhancement of the Casimir force. Second, the classical photoinduced stress must be considered. The increment of the carriers deforms silicon plate. Third, the electrostatic force caused by the residual charge on the silicon surface must be considered.

Figure 9. Schematic set up for the measurement of the change in the Casimir force.
5. Summary

The Casimir effect will be argued more widely in the future. Because the Casimir force becomes much stronger in the Nanoworld. We do not understand deeply the Casimir effect yet. Our theoretical analysis is only the first step to study the enhancement of the Casimir force and we incorporated several approximations which should be checked in the future. In real systems, we have to consider more complicated factors. First of all, it is necessary to extend Lifshitz theory to calculate the Casimir attraction between dielectric slabs with time depending dielectric constant. We also need to consider surface recombination and inhomogeneous of carrier distribution. Furthermore the classical electromagnetic force between silicon membrane such as photovoltage and increment of the temperature by irradiation are also important factors in an experiment. There are many problems which should be solved to manifest the enhancement of the Casimir force, but, its measurement is important to understand the Casimir force deeply and control the Casimir force optically.

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[1] H. B. G. Casimir: Proc. Kon. Ned. Akad. Wet. 51 (1948) 793.
[2] S. K. Lamoreaux, Phys. Today 60 (2007) 40.
[3] P. W. Miomni: The Quantum Vacuum (Academic Press, SanDiego 1994).
[4] M. Serry, D. Walliser and J. Maclay: J. App. Phys. 84 (1998) 2501.
[5] L. D. Landau and E. M. Lifshits: Electrodynamics of Continuous Media (Oxford Science Publications, SanDiego, 1982).
[6] W. Arnold, S. Hunklinger and K. Dransfeld: Phys. Rev. B. 19 (1979) 6049.
[7] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop and F. Capasso: Science 291 (2001) 1941.
[8] A. I. Volokitin, B. N. Persson: Phys. Rev. Lett. 91 (2003) 106101.
[9] N. Imi: J. Phys. Soc. Jpn., 73 (2006) 332.
[10] N. Imi: J. Phys. Soc. Jpn., 75 (2006) 024004.
[11] F. Zhou and L. Spruch: Phy. Rev. A 52 (1995) 297.
[12] R. Matloob: Phy. Rev. A 64 (2001) 042102.
[13] T. Vogel, G. Dodel, E. Holzhauer, H. Salzmann and A. Theurer: Applied Optics 31 (1992) 329.
[14] S. K. Lamoreaux: Phys. Rev. Lett. 78, (1997) 5.
[15] U. Mohideen and A. Roy: Phys. Rev. Lett. 81, (1998) 4549.