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Pulsating Casimir force

G L Klimchitskaya^{1,2}, U Mohideen³ and V M Mostepanenko^{1,4}¹ Center of Theoretical Studies and Institute for Theoretical Physics, Leipzig University, Postfach 100920, D-04009, Leipzig, Germany² North-West Technical University, Millionnaya St. 5, St Petersburg, 191065, Russia³ Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA⁴ Noncommercial Partnership 'Scientific Instruments', Tverskaya St. 11, Moscow, 103905, Russia

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Online at stacks.iop.org/JPhysA/40/F841**Abstract**

Based on the Lifshitz theory we show that the illumination of one (Si) plate in the three-layer systems Au–ethanol–Si, Si–ethanol–Si and α -Al₂O₃–ethanol–Si with laser pulses can change the Casimir attraction to Casimir repulsion and vice versa. The proposed effect opens novel opportunities in nanotechnology to actuate the periodic movement in electro- and optomechanical micromachines based entirely on the zero-point oscillations of the quantum vacuum without the action of mechanical springs.

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1. Introduction

Recent trends point towards an increased role of the Casimir effect in both fundamental physics and nanotechnology. The Casimir force [1] acts between two closely spaced neutral metallic plates. It arises due to the zero-point energy of the electromagnetic field. The Lifshitz theory [2] gave an accurate description of the material properties in the Casimir force and represented it as the retarded limit of the familiar van der Waals forces. According to current concepts, Casimir forces act between metals, insulators and semiconductors, between a molecule and a macrobody and between two molecules. In the last two cases they are usually referred to as the Casimir–Polder force. Multidisciplinary applications of the Casimir force and the first precise measurements are reviewed in [3]. Later experiments [4–14] stimulated the development of new theoretical methods applicable to more complicated configurations other than two static parallel plates [15–20]. The question whether the Casimir force is always attractive or it can also be repulsive, as was predicted for ideal metallic spherical and cubical shells [3], has been debated [21].

The applications of the Casimir force are promising in the design, fabrication and actuation of micro- and nanomechanical devices. When the characteristic sizes of a device shrink below

a micrometre, the Casimir force may become larger than typical electric forces. The first devices actuated by the Casimir force were demonstrated in [22, 23]. In [24, 25], the lateral Casimir force acting between corrugated surfaces was predicted. Later it was demonstrated experimentally [4, 5]. The lateral Casimir force was recently used to propose the Casimir-driven ratchets and pinions [26–28]. Considerable opportunities for micromechanical design would be opened by pulsating Casimir plates moving back and forth entirely due to the effect of the zero-point energy, without the action of mechanical springs. This can be achieved only through use of both attractive and repulsive Casimir forces. In this connection, it should be noted that while the repulsive Casimir forces for a single cube or a sphere are still debated the Casimir repulsion between the two parallel plates is well understood. Repulsion occurs when the plates with dielectric permittivities ε_1 and ε_2 along the imaginary frequency axis are immersed inside a medium with dielectric permittivity ε_0 such that $\varepsilon_1 < \varepsilon_0 < \varepsilon_2$ or $\varepsilon_2 < \varepsilon_0 < \varepsilon_1$ [29, 30]. At short separations in a nonretarded van der Waals regime this effect was discussed for a long time and measurements have been reported (see for example review [31] and one of the later experiments [32]).

In this paper, we consider three pairs of parallel plates immersed in ethanol. First pair includes Au and Si plates with the Si plate illuminated by light pulses from a laser. The second pair consists of two similar Si plates with one of them illuminated by light pulses. As was recently shown in [14], the illumination with light of appropriate power increases the charge carrier density in Si by several orders of magnitude and changes the dielectric permittivity over a wide frequency range along the imaginary frequency axis leading to the modulation of the Casimir force. In the third pair, one plate is made of α -Al₂O₃ and the other of Si. The latter plate is illuminated with laser pulses. For all pairs of plates we calculate the Casimir force per unit area as a function of separation distance. It appears that within a wide range of separations there is a repulsive Casimir force for the first pair of plates when the light is off and an attractive force when the light is on. For the second and third pairs of plates, the force is repulsive when the light is on and attractive when the light is off. Thus, we find for the first time that illumination with laser light can change Casimir attraction to Casimir repulsion and vice versa. By appropriately choosing the duration of the pulse and the time between pulses, it is possible to obtain pulsating Casimir plates.

2. Theoretical approach and dielectric permittivities

We consider the Casimir interaction between two plates with dielectric permittivities $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ immersed in ethanol with the dielectric permittivity $\varepsilon_0(\omega)$ at a temperature T in thermal equilibrium. The separation between the plates is a . The Casimir pressure is given by the Lifshitz formula [2, 3]

$$P(a, T) = -\frac{k_B T}{8\pi a^3} \sum_{l=0}^{\infty} \int_{\sqrt{\varepsilon_0 \zeta_l}}^{\infty} y^2 dy \times \left[\frac{1}{e^{y r_{\text{TM};1}^{-1}(\zeta_l, y)} r_{\text{TM};2}^{-1}(\zeta_l, y) - 1} + \frac{1}{e^{y r_{\text{TE};1}^{-1}(\zeta_l, y)} r_{\text{TE};2}^{-1}(\zeta_l, y) - 1} \right]. \quad (1)$$

Here, the dimensionless Matsubara frequencies, ζ_l , are related with dimensional ones, ξ_l , by $\zeta_l = 2a\xi_l/c = 4\pi k_B T a l / (\hbar c)$, $l = 0, 1, 2, \dots$, where k_B is the Boltzmann constant. The

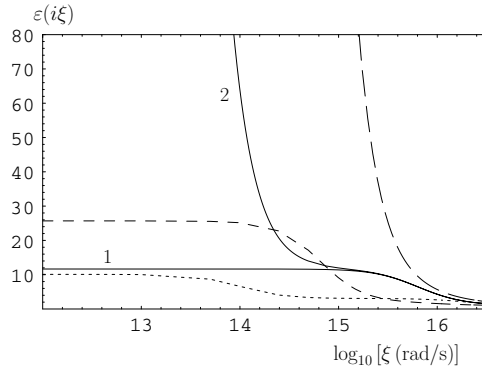


Figure 1. The dielectric permittivities of different materials along the imaginary frequency axis are shown with solid lines 1 and 2 for Si in the absence and in the presence of laser light, respectively, with a long-dashed line for Au, with a short-dashed line for ethanol and with a dotted line for α -Al₂O₃.

reflection coefficients on the 1st and 2nd plates for TM and TE polarizations are defined as

$$r_{\text{TM};1,2}(\zeta_l, y) = \frac{\varepsilon_{1,2}y - \varepsilon_0\sqrt{y^2 + (\varepsilon_{1,2} - \varepsilon_0)\zeta_l^2}}{\varepsilon_{1,2}y + \varepsilon_0\sqrt{y^2 + (\varepsilon_{1,2} - \varepsilon_0)\zeta_l^2}}, \quad (2)$$

$$r_{\text{TE};1,2}(\zeta_l, y) = \frac{\sqrt{y^2 + (\varepsilon_{1,2} - \varepsilon_0)\zeta_l^2} - y}{\sqrt{y^2 + (\varepsilon_{1,2} - \varepsilon_0)\zeta_l^2} + y},$$

where $\varepsilon_{1,2} = \varepsilon_{1,2}(i\xi_l)$, $\varepsilon_0 = \varepsilon_0(i\xi_l)$.

To calculate the Casimir pressure for the above three pairs of plates one needs the dielectric permittivities of Au, Si, α -Al₂O₃ and ethanol, $\varepsilon^{\text{Au}}(i\xi)$, $\varepsilon^{\text{Si}}(i\xi)$, $\varepsilon^\alpha(i\xi)$ and $\varepsilon_0(i\xi)$, along the imaginary frequency axis. For Au and dielectric Si (in the absence of laser light), the precise results for permittivities are computed in [33] by means of the tabulated optical data for the complex index of refraction [34] and Kramers–Kronig relation. The obtained permittivities are shown in figure 1 by the long-dashed line and solid line 1, respectively. For ethanol and α -Al₂O₃, the dielectric permittivities along the imaginary frequency axis can be presented in the Ninham–Parsegian approximation [29, 30, 35]:

$$\varepsilon^{(k)}(i\xi_l) = 1 + \frac{C_k^{\text{IR}}}{1 + \xi_l^2/\omega_{\text{IR},k}^2} + \frac{C_k^{\text{UV}}}{1 + \xi_l^2/\omega_{\text{UV},k}^2}, \quad (3)$$

where for ethanol $C_1^{\text{IR}} = 23.84$, $C_1^{\text{UV}} = 0.852$, $\omega_{\text{IR},1} = 6.600 \times 10^{14} \text{ rad s}^{-1}$, $\omega_{\text{UV},1} = 1.140 \times 10^{16} \text{ rad s}^{-1}$, and for α -Al₂O₃ it holds $C_2^{\text{IR}} = 7.03$, $C_2^{\text{UV}} = 2.072$, $\omega_{\text{IR},2} = 1.000 \times 10^{14} \text{ rad s}^{-1}$, $\omega_{\text{UV},2} = 2.000 \times 10^{16} \text{ rad s}^{-1}$. In figure 1, the dielectric permittivity of ethanol, $\varepsilon^{(1)}(i\xi_l) \equiv \varepsilon_0(i\xi_l)$, is shown by the short-dashed line, and the permittivity of α -Al₂O₃, $\varepsilon^{(2)}(i\xi_l) \equiv \varepsilon^\alpha(i\xi_l)$, is shown by the dotted line.

Careful attention should be paid to the influence of light pulses on the Si plate. A few micron thick single crystal membrane of (100) orientation can be used as a dielectric Si plate. The static dielectric permittivity of such a plate is equal to $\varepsilon^{\text{Si}}(0) \approx 11.66$ [33, 34] (see the solid line 1 in figure 1). When the light from an Ar laser is incident on the Si plate, the equilibrium number of charge carriers per unit volume is rapidly established, during a period of time much shorter than the duration of the pulse [14, 36]. The increase in the carrier

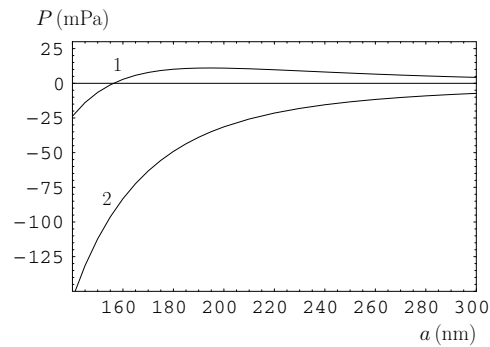


Figure 2. The Casimir pressure versus separation in a three-layer system Au–ethanol–Si with no light on the Si plate is shown by line 1 and with the illuminated Si plate is shown by line 2.

density on illumination can lead to electrostatic effects due to changes in the band bending at the semiconductor surface. Therefore, care must be taken to achieve flat bands by surface passivation.

Assuming that there is an equilibrium concentration of electrons and holes in the presence of light, we obtain the dielectric permittivity of Si in the form

$$\varepsilon_L^{\text{Si}}(i\xi_l) = \varepsilon^{\text{Si}}(i\xi_l) + \frac{(\omega_p^{(e)})^2}{\xi_l(\xi_l + \gamma^{(e)})} + \frac{(\omega_p^{(p)})^2}{\xi_l(\xi_l + \gamma^{(p)})}. \quad (4)$$

Here, $\omega_p^{(e,p)}$ and $\gamma^{(e,p)}$ are the plasma frequencies and relaxation parameters for electrons and holes, respectively. The values of the relaxation parameters and the effective masses of charge carriers are the following [36]: $\gamma^{(p)} \approx 5.0 \times 10^{12} \text{ rad s}^{-1}$, $\gamma^{(e)} \approx 1.8 \times 10^{13} \text{ rad s}^{-1}$, $m_p^* = 0.2063m_e$, $m_e^* = 0.2588m_e$. The values of the plasma frequencies can be found from the equation $\omega_p^{(e,p)} = (n_L e^2 / m_{e,p}^* \epsilon_0)^{1/2}$, where ϵ_0 is the permittivity of vacuum and n_L is the density of charge carriers of each type in the presence of light. The typical value of $n_L \approx 2.1 \times 10^{19} \text{ cm}^{-3}$ was found in [14] for a light power of about 3.4 mW absorbed on a surface area $\pi w^2/4$, where $w = 0.23 \text{ mm}$ is the diameter equal to the Gaussian width of the beam. Then one obtains $\omega_p^{(e)} \approx 5.08 \times 10^{14} \text{ rad s}^{-1}$ and $\omega_p^{(p)} \approx 5.69 \times 10^{14} \text{ rad s}^{-1}$.

3. Computational results

In figure 2, we present the computational results for the Casimir pressure versus separation distance between the first pair of plates, i.e., for Au and Si plates separated by ethanol, where Si is illuminated with laser pulses. These results are computed using equation (1) where $\varepsilon_1(i\xi_l) = \varepsilon^{\text{Au}}(i\xi_l)$, $\varepsilon_2(i\xi_l) = \varepsilon^{\text{Si}}(i\xi_l)$ in the absence of laser light and $\varepsilon_2(i\xi_l) = \varepsilon_L^{\text{Si}}(i\xi_l)$ in the presence of laser light. In both cases $\varepsilon_0(i\xi_l) \equiv \varepsilon^{(1)}(i\xi_l)$ is the permittivity of ethanol. The pressure–distance dependence in the absence of light on a Si plate is shown as line 1. As is seen in figure 2, for separations larger than 156 nm the Casimir pressure shown by line 1 is repulsive. This effect of repulsion in a three-layer system is well known [29–32]. It reflects the fact that in figure 1 the inequalities $\varepsilon^{\text{Si}}(i\xi) < \varepsilon_0(i\xi) < \varepsilon^{\text{Au}}(i\xi)$ are valid within a wide frequency range. These three permittivities are shown as the solid line 1, the short-dashed line and the long-dashed line, respectively. In particular, from equation (3) it follows that $\varepsilon_0(0) = 1 + C_1^{\text{IR}} + C_1^{\text{UV}} = 25.692 > \varepsilon^{\text{Si}}(0)$. The pressure–distance dependence in the presence of laser light on a Si plate is shown by line 2 in figure 2. This line corresponds to attraction

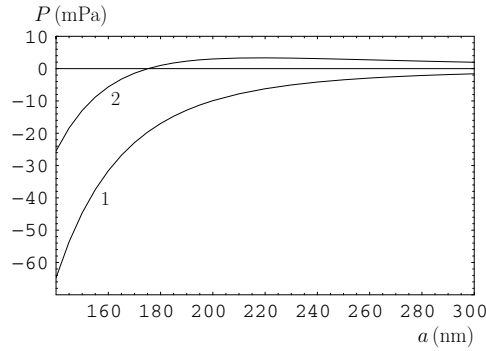


Figure 3. The Casimir pressure versus separation in a three-layer system Si–ethanol–Si with no light on both Si plates is shown by line 1 and with one illuminated Si plate is shown by line 2.

at all separation distances. The physical explanation of this fact can be obtained in figure 1 where the dielectric permittivity of Si in the presence of light (the solid line 2) $\varepsilon_L^{\text{Si}}(i\xi) > \varepsilon_0(i\xi)$ within a wide frequency region. Thus, the illumination of a Si plate with laser light changes the Casimir force from repulsion to attraction. Note that the above result does not depend on discussions in the literature (see, e.g., [37]) on the value of TE reflection coefficient of metals at zero frequency. The reason is that for insulators and semiconductors $r_{\text{TE};2}(0, y) = 0$ and thus the TE reflection coefficient of Au, $r_{\text{TE};1}(0, y)$, regardless of its magnitude, does not contribute to the Casimir pressure as it is multiplied by zero.

Now we consider the computational results for the Casimir pressure in the second pair of plates Si–ethanol–Si, where one of the Si plates is illuminated with laser pulses. In the absence of light $\varepsilon_1(i\xi_l) = \varepsilon_2(i\xi_l) = \varepsilon^{\text{Si}}(i\xi_l)$, where ε^{Si} is the permittivity of high resistivity Si. The permittivity of ethanol is $\varepsilon_0(i\xi_l) \equiv \varepsilon^{(1)}(i\xi_l)$ from equation (3). Substituting this into equation (1) we arrive at the pressure–distance relation shown in figure 3 by line 1. As is seen in figure 3, the respective Casimir pressure is attractive at all separations. This is expected from the outset because the permittivities of both plates are equal. Now let the second Si plate be illuminated with a laser pulse. Then in equation (1) the dielectric permittivity $\varepsilon_2(i\xi_l) = \varepsilon_L^{\text{Si}}(i\xi_l)$, where $\varepsilon_L^{\text{Si}}$ is defined in equation (4). In this case, the computational results for the Casimir pressure versus separation are shown by line 2 in figure 3. As is seen in the figure, at $a < 175$ nm the Casimir force is attractive, but at larger separations it becomes repulsive. The repulsion is explained by the fact that within a wide frequency range the inequalities $\varepsilon^{\text{Si}}(i\xi) < \varepsilon_0(i\xi) < \varepsilon_L^{\text{Si}}(i\xi)$ hold. Thus, illumination with light leads to a change from Casimir attraction to Casimir repulsion in the system of two Si plates separated by ethanol.

In the previously considered cases, the magnitudes of the repulsive forces were several times less than the magnitude of the attractive forces. However, it is possible to design a case where the light-induced Casimir repulsion is of the same order of magnitude as the attraction. A good example is given by the three-layer system $\alpha\text{-Al}_2\text{O}_3$ –ethanol–Si, where the Si plate is illuminated with laser pulses (the third pair of plates). First, we perform the computations of the Casimir pressure using equation (1) in the absence of laser light. In this case $\varepsilon_1(i\xi_l) = \varepsilon^{(2)}(i\xi_l) \equiv \varepsilon^\alpha(i\xi_l)$, where the dielectric permittivity ε^α of $\alpha\text{-Al}_2\text{O}_3$ is defined in equation (3), $\varepsilon_2(i\xi_l) = \varepsilon^{\text{Si}}(i\xi_l)$ and $\varepsilon_0(i\xi_l) \equiv \varepsilon^{(1)}(i\xi_l)$ from equation (3) is the dielectric permittivity of ethanol. The computational results for the Casimir pressure versus separation distance are shown by line 1 in figure 4. It can be observed that the Casimir force is attractive as expected because within a wide frequency range both dielectric permittivities of Si, $\varepsilon^{\text{Si}}(i\xi)$,

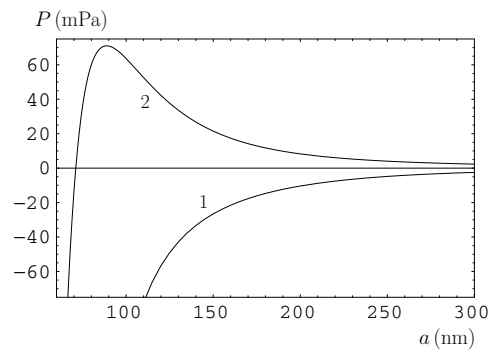


Figure 4. The Casimir pressure versus separation in a three-layer system α -Al₂O₃–ethanol–Si with no light on the Si plate is shown by line 1 and with the illuminated Si plate is shown by line 2.

and of α -Al₂O₃, $\varepsilon^\alpha(i\xi)$, are smaller than the dielectric permittivity of ethanol $\varepsilon_0(i\xi)$ (see figure 1). For example, the static dielectric permittivity of α -Al₂O₃, as given by equation (3), is $\varepsilon^\alpha(0) = 1 + C_2^{\text{IR}} + C_2^{\text{UV}} = 10.102 < \varepsilon_0(0)$.

Now let the Si plate be illuminated with the laser pulse. In this case, we substitute into equation (1) $\varepsilon_2(i\xi_l) \equiv \varepsilon_L^{\text{Si}}(i\xi_l)$, as defined in equation (4), and with the other two permittivities kept unchanged. The computational results for the Casimir pressure versus separation distance are shown by line 2 in figure 4. As is seen from the figure, at separations $a > 71.5$ nm the corresponding Casimir force is repulsive. Remarkably, in this case the Casimir repulsion and attraction are of the same order of magnitude within a wide range of separations. Thus, the third pair of plates provides an example where the illumination of the Si plate changes the Casimir attraction to a repulsive force of the same order. For the observation of the pulsating Casimir force we envision that the plates would be completely immersed in the liquid far away from any air–liquid interfaces, thus, preventing the occurrence of capillary forces. Surface preparation of the plates will be necessary to bring about intimate contact between the plates and the liquid. The only liquid-based force is the drag force due to the movement of the plates in response to the change in the force. For pressure values of around 10 mPa and typical spring constants of 0.02 N m^{-1} , the corresponding drag pressure from plate movement would be six orders of magnitude less in value.

4. Conclusions and discussion

In the above we have shown that the illumination of one of the plates in a three-layer Casimir system can change the repulsion to attraction and vice versa entirely due to the modification of the spectrum of the quantum vacuum. This is attained by the combination of the familiar properties of three-layer systems [29] and the recently demonstrated modulation of the Casimir force with laser light [14]. The proposed effect of the pulsating Casimir force can be used to actuate the periodic movement of electrodes and mirrors in electro- and optomechanical micromachines. This can be achieved by using the standard frequency generators and modulators to select the appropriate duration and time between the laser pulses. For the case of ethanol considered here the hydrodynamic and viscous effects will limit the operational bandwidth of the actuators to around 10 MHz for a plate size of $10 \times 10 \mu\text{m}^2$. Here, the deviations from plate parallelism of less than 0.2° (which is experimentally achievable) would lead to a less than 3% change in the value of the Casimir pressure computed above [3] with no change in its sign. The pulsating Casimir force will also find applications in

nanotechnology for controlling the efficiency and increasing the operational bandwidth of microswitches, micromirrors and nanotweezers.

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