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Intensifying the Casimir force between two silicon substrates within three different layers of materials

A. Seyedzahedi [a], A. Moradian [b,*], M.R. Setare [a]

[a] *Department of Science, University of Kurdistan, Sanandaj, Iran*
[b] *Department of Science, Campus of Bijar, University of Kurdistan, Bijar, Iran*

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ABSTRACT

We investigate the Casimir force for a system composed of two thick slabs as substrates within three different homogeneous layers. We use the scattering approach along with the Matsubara formalism in order to calculate the Casimir force at finite temperature. First, we focus on constructing the reflection matrices and then we calculate the Casimir force for a water–lipid system. According to the conventional use of silicon as a substrate, we apply the formalism to calculate the Casimir force for layers of Au, VO_2, mica, KCl and foam rubber on the thick slabs of silicon. Afterwards, introducing an increasing factor, we compare our results with Lifshitz force in the vacuum between two semispaces of silicon in order to illustrate the influence of the layers on intensifying the Casimir force. We also calculate the Casimir force between two slabs of the forementioned materials with finite thicknesses to indicate the substrate's role in increasing the obtained Casimir force. Our simple calculation is interesting since one can extend it along with the Rigorous Coupled Wave Analysis to systems containing inhomogeneous layers as good candidates for designing nanomechanical devices.

1. Introduction

The Casimir effect [1], resulting from modifying the vacuum fluctuations due to the insertion of the boundaries, has entered a new era of novel accurate measurements. According to the rapid progress of the nanotechnology, the Casimir force has been introduced to offer new possibilities for designing nanomechanical systems [2,3]. The Lifshitz formula for two dielectric semispaces at arbitrary temperature has been investigated providing the Casimir force for real bodies in [4]. Considering two periodic dielectric gratings, Lambrecht and Marachevsky have presented an exact calculation to obtain the Casimir energy in [5]. It is worth mentioning that the comparison between their theoretical calculations and the measurements performed by Chan et al. [6] for grating-sphere geometry, manifests a meaningful agreement. Based on the scattering approach [7–11], the researchers have investigated the finite temperature Casimir interaction force between two periodic nanostructures using the modal approach in [12] and they have also illustrated the flexibility of this formalism. The Casimir energy between a plate and a nanostructured surface at arbitrary temperature has been calculated in the framework of the scattering theory in [13] and as a significant consequence of this investigation, it is illustrated that for grating geometries the contribution of the thermal part of the Casimir energy is intensified at small separation distances. Modeling grating as a dielectric function depending on the space and frequency as well as using a variable phase method, Graham in [14] has presented an appropriate approach to investigate the Casimir effect for gratings with deep corrugations. In 2007, utilizing an analysis of the phase shift of the vacuum fields due to propagating through the materials, Lambrecht et al. have presented a detailed calculation for the Casimir force between silicon and gold slabs of different thicknesses with respect to both Drude and plasma models for the dielectric function of gold [15]. Several studies are done with the purpose of investigating the influence of the slab thicknesses on the Casimir effect, of which we are going to mention some: In [16], Klimchitskaya and Mostepanenko have studied the Casimir energy for metallic films between dielectric plates. They have also performed numerical calculations for Au thin films in vacuum or sandwiched between two semispaces of sapphire. In addition to the main subject of the study that is the Casimir force between slabs of intrinsic and doped silicon, Pirozhenko and Lambrecht in [17] have performed numerical computations for a VO_2 film on a sapphire substrate with a gold layer on the silicon slab. Using the Drude–Smith model for the dielectric function of Au thin films, Sirvent

* Corresponding author.
E-mail addresses: a.moradian@uok.ac.ir (A. Moradian), rezakord@ipm.ir (M.R. Setare).

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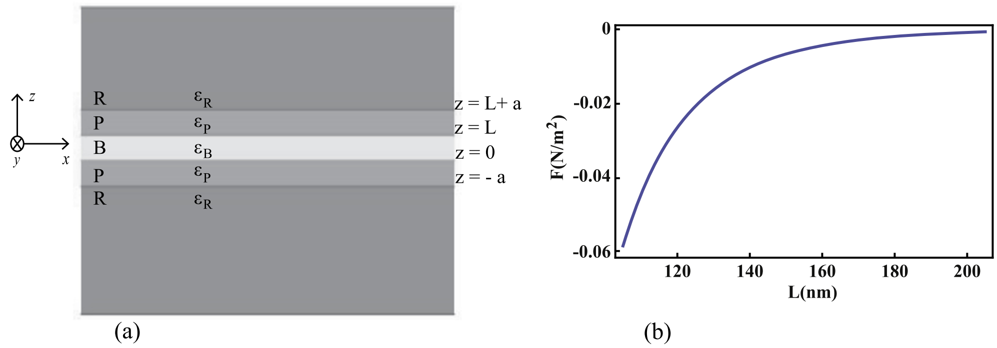

Fig. 1. (a) A system composed of two half spaces of a material characterized with the permittivity $\varepsilon_R(\omega)$ as substrates within three alternating homogeneous layers described by permittivities $\varepsilon_B(\omega)$ and $\varepsilon_P(\omega)$. (b) Plot of the Casimir interaction force per unit area as a function of separation distance L for the configuration of Fig. 1(a) at $T = 300$ K. Here we have considered water and lipid for the alternating layers with $a = 4$ nm as the thickness of medium P.

has investigated the Casimir force between these films near the critical thickness in [18].

In this work, we want to investigate intensifying the Casimir force due to the presence of a layer on the substrate. For this purpose, we consider two semispaces as substrates and a symmetric array composed of three homogeneous layers of alternating materials in between as depicted in Fig. 1(a). To start the study, we assume the semispaces to be water and the alternating layers in between to be water and lipid. Considering the advantages of the scattering approach including that the divergency occurring in calculating the Casimir energy does not appear in the scattering formalism as well as the fact that with the advent of this approach, the efficient evaluation of the Casimir effect has been made possible, we initiate from a scattering approach along with the Matsubara formalism to determine the Casimir force for Fig. 1(a) at finite temperature. First, introducing longitudinal components of the electric and magnetic fields, we impose the continuity boundary condition and focus on the construction of reflection matrices for the profile of Fig. 1(a) and then, we calculate the Casimir force for the forementioned water–lipid system as an instance that is in a good agreement with the results evaluated by Podgornik and his colleagues in [19,20]. They have obtained this result for the interaction of two isolated lipid layers when they have explored the nonadditivity of the Casimir effect in the multilamellar geometries applying an algebra of 2×2 matrices. Afterwards, we concentrate on the main part of the investigation which is exploring the effect of the layers on intensifying the Casimir force. For this purpose, assuming the importance of silicon in constructing miniaturized electromechanical devices and its conventional use as a substrate, we consider layers of different materials including Au, VO_2, mica, KCl, and foam rubber (as a dilute media) on thick slabs of silicon and calculate the Casimir force in the inner medium of Fig. 1(a) which is supposed to be vacuum. Results of our calculations illustrate that increasing the layer thickness yields into a downward trend in the value of the Casimir force for insulators; however, it results in increasing the Casimir force for Au. Introducing the increasing factor r, we perform a comparison between our results and the Lifshitz force between two thick slabs of silicon in the same separation distance, with the purpose of investigating the effect of the layers on intensifying the casimir force. According to our calculations, in spite of the downward trend of the Casimir force for insulators, this increasing factor (r) is greater than one for all of the investigated layers. Our calculations depict that, this increasing factor grows as a result of increasing the thickness of the layers and that in the case of having materials with greater zero frequency permittivities, this intensification occurs significantly. We also calculate the Casimir force between two similar slabs with finite thicknesses to indicate the role of substrates in increasing the Casimir force. Our results of depicting the intensification of the Casimir force due to the presence of a layer, even a nanometer-thick layer, on the substrate would be applicable for experimental studies of the Casimir effect and also for designing nanomechanical devices driven by the Casimir force. It is worth mentioning that, the scattering approach which allows one to consider non-trivial geometries at finite temperature together with a realistic description of the material properties, permits us to calculate the Casimir energy for a configuration with a periodic structure in its layers (i.e. inhomogeneous configuration). This approach along with the Rigorous Coupled Wave Analysis (RCWA) method [5,13,21] enables us to investigate such a configuration in future with the purpose of utilizing that in designing nanomachines.

2. Constructing reflection matrices

Let us consider two half-space mediums with a symmetric array composed of three layers of alternating materials in between, as depicted in Fig. 1(a). B, i.e. the inner homogeneous region, is the one defined as the medium in $0 < z < L$ with the permittivity $\varepsilon_B(\omega)$. Over this, there exists another homogeneous region, $L < z < L + a$, labeled P with the permittivity $\varepsilon_P(\omega)$ and above that we have an R-labeled homogeneous region characterized by the permittivity $\varepsilon_R(\omega)$. Below region B, in $-a < z < 0$, symmetric to the upper half of Fig. 1(a), there is another medium P described with the permittivity $\varepsilon_P(\omega)$ and under that we have another R-region characterized by $\varepsilon_R(\omega)$.

We assume a plane wave propagating along the z-axis which is reflected and transmitted through the nearby layers. Considering that this configuration is t, x and y invariant, we can extract a factor $e^{i(k_x x + k_y y - \omega t)}$ from all components of the electromagnetic fields. In the absence of the upper half of Fig. 1(a), we introduce the y-components of the electric and magnetic fields in the medium B as:

$$\begin{cases} E_y^B = I_B^e e^{-i\gamma_B z} + R_B^e e^{i\gamma_B z} \\ H_y^B = I_B^h e^{-i\gamma_B z} + R_B^h e^{i\gamma_B z} \end{cases} \tag{1}$$

where $I_B^{e(h)}$ and $R_B^{e(h)}$ are the incident and reflection coefficients of the electric (magnetic) waves. γ_B indicates the z-component of the wave vector in the medium B, which can be introduced for the medium $j = B$, P or R as

$$\gamma_j = i\left(-\varepsilon_j(\omega)\frac{\omega^2}{c^2} + k_x^2 + k_y^2\right)^{1/2} \tag{2}$$

In this relation ω is the frequency, c denotes the speed of light and k_x and k_y are the longitudinal components of the wave vectors. We assume the relative permittivity of the region $\varepsilon_j(\omega)$ as a function of frequency including dissipation.