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Quantum levitation of photonic structures

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Abstract. The Casimir-Lifshitz force originates from the quantum vacuum fluctuations of the electromagnetic field. This force is especially intense between interacting objects at nanoscale distances, and it can be attractive or repulsive depending on the optical properties of the materials (amongst other parameters). This fundamental phenomenon is at the heart of the malfunctioning of nano- and micro-electromechanical devices (NEMS and MEMS) that integrate many of the gadgets we use in our daily lives. Absolute control over these forces would make it possible to suppress adhesion and friction in these NEMs and MEMs. Here, we will show the possibility of controlling the Casimir-Lifshitz force by tuning the optical properties of the interacting objects. Specifically, we will present diverse examples of quantum levitation based on the Casimir-Lifshitz force of self-standing thin films comprising multilayer structures and films with spatial inhomogeneities (caused by imperfections, pores, inclusions, density variations, etc).

As it follows from the extended Lifshitz theory, the nature (attractive or repulsive) and intensity of the Casimir-Lifshitz force ($F_{(C-L)}$) depend, amongst others, on the optical properties of the interacting materials [1].

Here we show theoretically how a fine tuning of the materials optical properties allows modifying $F_{(C-L)}$ in a controlled manner, and in turn, the quantum trapping of planar strutures. The selected materials (polystyrene (PS), silicon dioxide (SiO_2), silicon (Si), and glycerol) display remarkable optical quality, experimentally manageable thicknesses, and unlike alcohols, stable dissipation properties. Based on previous results where we showed that thin films of SiO_2 and PS facing the same Si substrate in glycerol display $F_{(C-L)}$ of different sign and comparable intensity [2], we create photonic structures that combine such materials in either multilayer structures (ML) [3] or in composites [4], to modulate $F_{(C-L)}$ and the corresponding quantum trapping of such structures.

Results and Discussion

To calculate $F_{(C-L)}$, we employ the Lifshitz's theoretical formalism expressed for an arbitrary layered system [5]. In the case of multilayer structures, optical properties are computed by means of the Transfer Matrix Method formalism [6,7], while for nanocomposites (i.e, a homogeneous matrix embedding spherical nanoinclusions), our developed approach is based on the Monte Carlo method, which integrates Fresnel coefficients, and scattering Mie theory. The complex effective dielectric permittivity of the inhomogeneous material,

$$\varepsilon_{eff}(\omega) = \varepsilon'_{eff}(\omega) + \varepsilon''_{eff}(\omega) \qquad (1)$$

is then extracted in a reverse process using an oscillatory model that fits the optical characteristics of the composite material. The resulting value of $\varepsilon_{eff}(\omega)$ is employed to calculate $F_{(C-L)}$ when the object approaches a substrate.

First, we spot a physical mechanism that enables the manipulation of $F_{(C-L)}$ in multilayer dielectric nanostructures due to optical interference effects (Fig. 1a). Optical interference effects yield high electric-field localization within the nanostructure, which in turn reshapes the partial absorptance of the constituent materials at the UV frequency range, modifying the $F_{(C-L)}$ experienced by the system. Figure 1b shows the spectral and spatial absorption per unit volume, δA, for a multilayer structure of 40 nm total thickness, comprising 50% of SiO_2 and 50% of PS arranged in 2 bilayers, immersed in glycerol over a Si substrate. We find that strong absorption modifications within the multilayer structure due to light trapping inside the system at UV frequencies allow to tune $F_{(C-L)}$ by keeping the material volume constant and stratifying it in different number of bilayers.

Second, we examine composite materials in which an otherwise homogeneous SiO_2 film contains PS nanospherical inclusions of different size and concentration. These nanoinclusions could account for the presence of imperfections, pores, inclusions, or density variations in real materials. In this case, we propose an effective medium approximation that accounts for the effect of inclusions and find that an unprecedented and counterintuitive intense repulsive Casimir−Lifshitz force arises as a result of the strong optical scattering and absorption size-dependent resonances caused by their

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presence. Our results imply that the proper analysis of quantum trapping effects requires comprehensive knowledge and a detailed description of the potential inhomogeneity present in the materials. Figure 2 shows the effective dielectric function, in Matsubara frequencies, attained for a 1000 nm thick SiO_2 film containing 10% of nanospherical PS inclusions using our developed approach in which photon resonances are taken into account (in green). Contrary to effective medium approximations such as the Maxwell-Garnett model, which neglect photon resonances of nanoinclusions (in grey), here we demonstrate that the effects of scattering on optically dense inclusions lead to a decrease in the effective dielectric function when the radius of the inclusions increases (Fig. 2a). This counterintuitive effect, that does not agree with the predictions of effective medium approach, gives rise to a less attractive $F_{(C-L)}$ at short separation distances, bringing the system to larger quantum trapping distances (Fig. 2b).

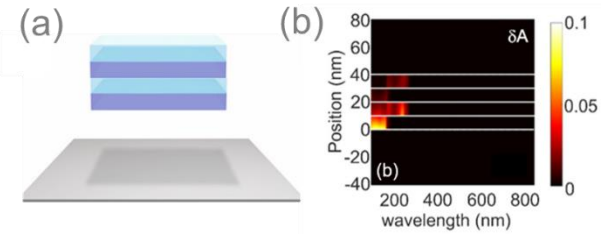

Fig. 1. (a) Schematics of a multilayer structure made of SiO_2 and PS slab bilayers, immersed in glycerol over a Si substrate. (b) Spectral and spatial distribution of absorption per unit volume, δA, of a representative example of a multilayer made of 2 bilayers. The specific geometrical parameters are: nanostructures comprising 50% SiO_2 and 50% PS, with a total thickness of 40 nm distributed in 2 bilayers (i.e., each layer thickness corresponds to 10 nm), immersed in glycerol with the SiO_2 layer facing a Si wall. As a guide for the eye, limits of each material layer of 10 nm thickness are shown with horizontal lines.

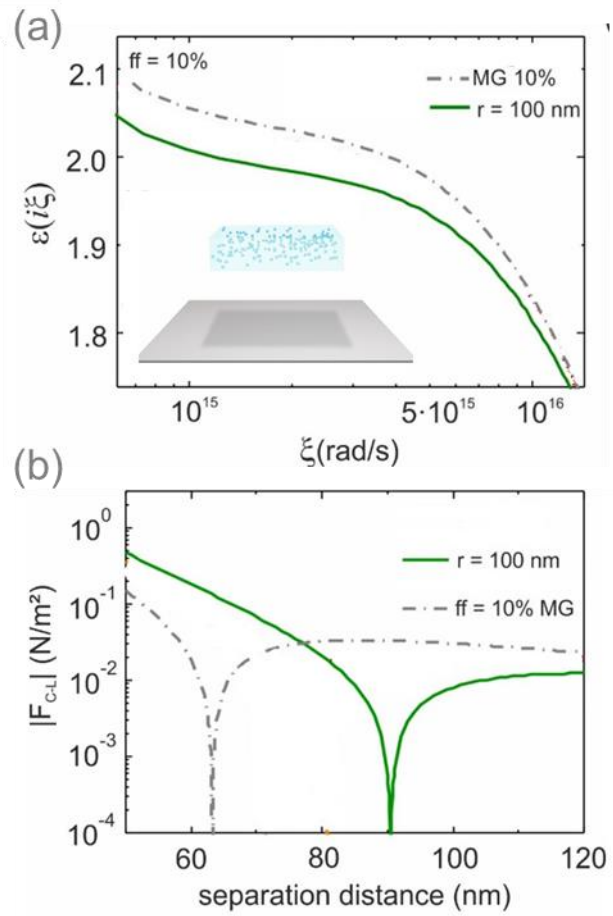

Fig. 2. (a) Effective dielectric function, evaluated at Matsubara frequencies, of a 1000 nm thick SiO2 film with PS nanospherical inclusions of radious r = 100 nm, in a 10% volume concentration (in green). For comparison, results attained using the Maxwell-Garnett effective medium approximation are shown in grey. (b) $F_{(C-L)}$ attained for the same system as in panel (a), when the composite material is immersed in glycerol and faces a Si substrate. Results obtained with our novel approach and using the Maxwell-Garnett method are depicted in green and grey colors, respectively.

Conclusions

We have shown that it is possible to control and manipulate $F_{(C-L)}$ through the optical properties of the interacting materials in the plane-parallel configuration. On the one hand, nanostructuring the same volume of dielectric materials in diverse multilayer configurations allows accessing $F_{(C-L)}$ of attractive or repulsive nature due to optical interference effects that alter the absorption losses of the multilayer. On the other hand, have shown that quantum trapping is strongly dependent on the characteristics of the potential and, likely, spatial inhomogeneity present in the system (porosity, impurities, nanoinclusions, etc), as the photon resonances they present, alter significantly the absorption properties of the composite material, and thus, the $F_{(C-L)}$. These results are of potential interest in the design and development of novel strategies to reduce malfunctioning of NEMs and MEMs.

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