Quantum levitation in nanowire materials

S. I. Maslovski and M. G. Silveirinha

Departamento de Engenharia Electrotécnica, Instituto de Telecomunicações, Universidade de Coimbra, Pólo II, 3030-290 Coimbra, Portugal, email: stas@co.it.pt, mario.silveirinha@co.it.pt

Abstract

In this work we demonstrate how the Casimir repulsion mechanism proposed by Boyer (the repulsion between a perfect electric and a perfect magnetic conductor) can be mimicked within a structure formed by cut silver nanorods. In particular, we consider a metallic piston that is perforated by vertical nanorods and may slide on them, and show that the repulsive Casimir force exerted on the piston in this structure is strong enough to prevent the piston from falling off the nanorods.

The Casimir force is a kind of interaction that appears virtually out of nothing: one can place an uncharged metallic body in a close proximity of another uncharged metallic body in a vacuum and notice that the bodies attract with a tiny, but measurable force. This elusive force originates from the quantum fluctuations of the electromagnetic field which, due to the uncertainty principle, exist in the gap separating the bodies even at the absolute zero of temperature. Since the theoretical discovery of this effect by Casimir in 1948, these purely quantum interactions have been subject of a continuous interest, with constantly emerging findings that bring out new knowledge as well as pose new questions.

One of the intriguing features of these quantum fluctuation-induced interactions is that they are not as straightforward as normal electrostatic or gravitational interactions: in general, one may not split the bodies into parts, solve separate problems, and then superimpose Casimir's forces acting in each subsystem to find the resulting total force. Instead, the interaction depends strongly on the geometry of the bodies and the electromagnetic conditions at their surface *as a whole*, so that in each and every new configuration the force has to be calculated from the scratch. The Casimir force may as well change sign depending on the geometry and (or) the electromagnetic properties of the bodies. Originally, Casimir found that the force between two electrically conducting plates was attractive. Later, Boyer [1] showed that the force may be repulsive if a conducting plate in the original Casimir configuration is replaced by a permeable plate. It is also known that the Casimir force between two dielectric bodies of certain permittivities can be made repulsive if the bodies are immersed in a fluid of an intermediate permittivity.

The permeable plate considered by Boyer was essentially a magnetic wall, or, in other words, a perfect magnetic conductor (PMC) at which the tangential magnetic field vanishes independently of the frequency of the field. Such surfaces, if available, would revolutionize electrodynamics, in a much similar manner as existence of magnetic monopoles would revolutionize physics. Unfortunately, it is the common knowledge that even with the use of metamaterials a PMC condition may be achieved only in a limited range of frequencies in a vicinity of a resonance. One could still try to find out if the known narrowband PMC realizations might allow for the Casimir repulsion of Boyer's type. However, the answer is negative because only the metamaterial response at relatively low imaginary frequencies affects the Casimir force, and at these frequencies all metal-dielectric metamaterials lose the magnetic properties they may have at real frequencies.

From the above discussion one may think that the metamaterial route to the Casimir repulsion of Boyer's type is completely blocked. However, our recent studies of ultralong-range Casimir forces in structures

ISBN 978-952-67611-0-7

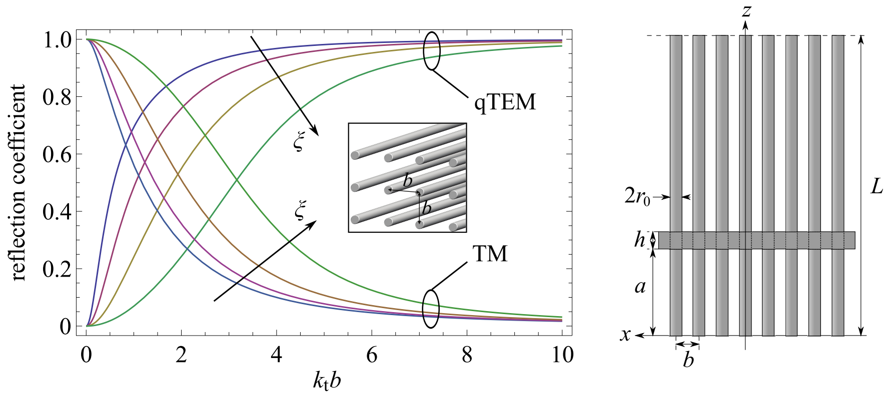

Fig. 1: Left: Reflection coefficients for the TM and the qTEM waves incident on an interface of an array of cut silver nanorods with air from within the nanorods. The plotted reflectivities are for the imaginary frequencies $\omega = i\xi$, with the following values for the parameter $b\xi/c$: 0.25, 0.5, 1, and 2, where b is the lattice constant (see the inset) and c is the speed of light. The direction of increasing ξ is indicated by the arrows. In the calculations, $b = 200$ nm, and the nanorod radius is $r_0 = 0.1b$. Right: A metallic piston of thickness h suspended by the repulsive Casimir force at height a above the open ends of cut metallic nanorods of length L. While the piston can freely slide on the nanorods, it does not fall off the nanorods.

formed by metallic nanorods [2] helped us to realize that if the conditions seen from within a metamaterial (and not from within a vacuum!) are of importance, then the situation can be dramatically different.

So far researchers have been considering systems in which the Casimir interaction happens in a vacuum, or within an isotropic dielectric. However, if such interactions occur within extremely anisotropic backgrounds, the Casimir force can be enhanced by many orders of magnitude. Moreover, within uniaxial crystals of metallic nanorods, the Casimir forces are ultralong-range: they decay inversely proportional to the second power of the distance, while in an isotropic background or a vacuum the force is inversely proportional to the fourth power of the same separation. This is because a uniaxial crystal of metallic nanorods supports (quasi)-transverse electromagnetic (qTEM or TEM) waves that resemble very much the modes of a multiwire transmission line. The metallic nanorods guide these waves very efficiently. Therefore, at large separations the Casimir force remains strong and is mostly due to the fluctuations associated with these long-range modes, which exist neither in vacuum, nor in isotropic dielectrics.

Exactly the same analogy with a multiwire transmission line helps discovering a way how to mimic a PMC condition within a nanowire background. Consider for simplicity a two-wire transmission line with a TEM wave propagating in it. Let us now abruptly cut the wires and let the wave be reflected by the open ends of the wires. As the line current and the magnetic field must vanish at the wire ends, the line voltage and the electric field must have a maximum at the same point. Thus, the reflected wave is in phase with the incident one, and the reflection coefficient for the TEM mode in this scenario equals $+1$ and is independent of the frequency (the radiation and the end effects may be neglected at low frequencies), which is the same behavior that one would require from an idealized magnetic wall. The real situation in nanowires is slightly more complicated, but this simple analogy remains qualitatively correct for the qTEM waves with large transverse wavenumbers k_t, as is seen from Fig. 1, left.

Therefore, the Casimir repulsion of Boyer's type may be mimicked with a structure shown in Fig. 1, right. This is an array of vertically aligned cut metallic nanorods with an embedded metallic piston that is perforated by the nanorods and can freely slide up and down on them. The nanorods are fixed at the top ends. The open ends of the nanorods at the bottom form an interface at which the fluctuating qTEM modes that exist within the structure are reflected as from a magnetic wall. The same modes reflect from the bottom side of the piston as from an electric wall, and in this way the Boyer's type Casimir interaction is mimicked, with the important difference that the resulting repulsive force in the nanorod background is much stronger at large separations as compared to the vacuum-separated case considered by Boyer.

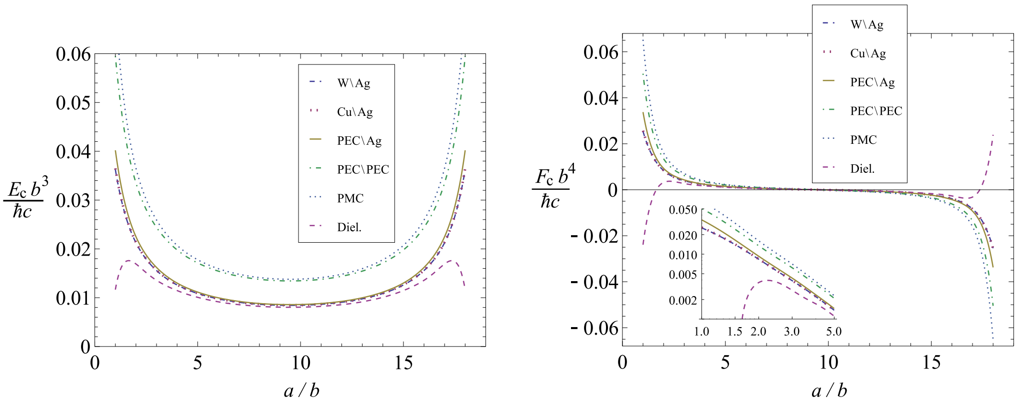

Fig. 2: Left: The normalized Casimir interaction energy in the system shown in Fig. 1 as a function of the relative separation a/b. Right: The normalized Casimir force on metallic and PEC pistons in the structure shown in Fig. 1 as a function of the relative separation a/b. The sign of the force is defined with respect to the z-axis. The inset shows the same force in logarithmic scale, for the range of separations $1 \le a/b \le 5$, which confirms the characteristic $1/a^2$ decay of the force. The following combinations are considered: W$\backslash$Ag — tungsten piston sliding on silver nanorods, Cu$\backslash$Ag — copper piston sliding on silver nanorods, PEC$\backslash$Ag — PEC piston sliding on silver nanorods, PEC$\backslash$PEC — PEC piston sliding on PEC nanorods, PMC — PEC piston sliding on PEC nanorods with ideal PMC walls at $z = 0$ and $z = L$. The values of the parameters are $b = 200$ nm, $r_0 = 0.1b$, $L = 20b$, $h = b$ (see Fig. 1).

An accurate analytical theory of the Casimir forces in this structure is rather complicated and lengthy, therefore we will not elaborate on it here. All details can be found in our recent paper [3]. The developed theory allows computing of the Casimir energy and force in structures composed of realistic lossy and dispersive metallic nanorods, as well as pistons that can be partially transparent or fully reflecting.

The Casimir energy in the structure shown in Fig. 1, right, calculated with the theory developed in [3] is represented in Fig. 2, left. We have considered several combinations of realistic and perfectly conducting (PEC) pistons and found that the open ends of the nanorods mimic the PMC condition quite closely. One may see that the energy has a minimum when the piston is in the middle of the structure. At this point the Casimir force (shown in Fig. 2, right) vanishes, and thus, if the wires were horizontal this point would be the point of a stable equilibrium. In such configuration, if the piston were shifted from the middle position, there would immediately appear a repulsive force that would return the piston back to the equilibrium point.

With vertically aligned nanorods, the equilibrium is reached when the Casimir repulsive force exerted on the piston equals the gravitational force. Our calculations show that a tungsten piston with thickness of 200 nm does not fall off the open ends of the nanorods in this configuration and will be suspended at the height of about 1 μm. Thus, the ultralong-range repulsive Casimir forces in a background formed by cut metallic nanorods are strong enough to levitate objects at heights approaching the macroscopic scale.

References

[1] T.H. Boyer, Van der Waals forces and zero-point energy for dielectric and permeable materials, *Physical Review A*, vol. 9, no. 5, pp. 2078–2084, 1974.
[2] S.I. Maslovski and M.G. Silveirinha, Ultralong-range Casimir-Lifshitz forces mediated by nanowire materials, *Physical Review A*, vol. 82, no. 2, pp. 022511(1–7), 2010.
[3] S.I. Maslovski and M.G. Silveirinha, Mimicking Boyer's Casimir repulsion with a nanowire material, *Physical Review A*, vol. 83, no. 2, pp. 022508(1-13), 2011.

ISBN 978-952-67611-0-7