

# Optical Chopper Driven by the Casimir Force

Mostepanenko V., Petrov V., Tschudi T.

Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

---

## Abstract

© 2018 American Physical Society. We propose an experimental scheme and present detailed theoretical description of the optical chopper in which functionality is based on the balance between the Casimir and light pressures. The proposed device consists of two atomically thin metallic mirrors forming the Fabry-Perot microfilter. One of the mirrors is deposited on a solid cube and another on a thinner wall subjected to bending under the influence of attractive Casimir force and repulsive force due to the pressure of light from a continuous laser amplified in the resonator of a microfilter. The separation distance between the mirrors should only slightly exceed the half wavelength of the laser light. It is shown that in this case the resonance condition in the microfilter alternatively obeys and breaks down resulting in the periodic pulses of the transmitted light. The Casimir pressure is calculated taking into account an anisotropy of the dielectric permittivity of a metal at several first Matsubara frequencies. The reflectivity properties of atomically thin metallic mirrors in the optical spectral range are found using the experimentally consistent phenomenological approach developed earlier in the literature. The specific values of all parameters, found for the microfilter made of quartz glass with Ag mirrors, demonstrate its workability. The proposed optical chopper may find prospective applications in the emerging field of nanotechnology exploiting the effects of quantum fluctuations.

<http://dx.doi.org/10.1103/PhysRevApplied.10.014010>

---

## References

- [1] J. J. Allen, *Micro Electro Mechanical System Design* (CRC Press, New York, 2005).
- [2] Y. Srivastava, A. Widom, and M. H. Friedman, *Microchips as Precision Quantum-Electrodynamic Probes*, *Phys. Rev. Lett.* 55, 2246 (1985). 0031-9007 10.1103/PhysRevLett.55.2246
- [3] Y. Srivastava and A. Widom, *Quantum electrodynamic processes in electrical-engineering circuits*, *Phys. Rep.* 148, 1 (1987). 0370-1573 10.1016/0370-1573(87)90020-2
- [4] V. A. Parsegian, *Van der Waals Forces: A Handbook for Biologists, Chemists, Engineers, and Physicists* (Cambridge University Press, Cambridge, 2005).
- [5] M. Bordag, G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, *Advances in the Casimir Effect* (Oxford University Press, Oxford, 2015).
- [6] F. M. Serry, D. Wallicer, and G. J. Maclay, *The anharmonic Casimir oscillator (ACO)-The Casimir effect in a model microelectromechanical system*, *J. Microelectromech. Syst.* 4, 193 (1995). 1057-7157 10.1109/84.475546
- [7] G. Palasantzas, *Contact angle influence on the pull-in voltage of microswitches in the presence of capillary and quantum vacuum effects*, *J. Appl. Phys.* 101, 053512 (2007). 0021-8979 10.1063/1.2472651
- [8] G. Palasantzas, *Pull-in voltage of microswitch rough plates in the presence of electromagnetic and acoustic Casimir forces*, *J. Appl. Phys.* 101, 063548 (2007). 0021-8979 10.1063/1.2711409
- [9] E. Buks and M. L. Roukes, *Stiction, adhesion, and the Casimir effect in micromechanical systems*, *Phys. Rev. B* 63, 033402 (2001). 0163-1829 10.1103/PhysRevB.63.033402

- [10] E. Buks and M. L. Roukes, Metastability and the Casimir effect in micromechanical systems, *Europhys. Lett.* 54, 220 (2001). 0295-5075 10.1209/epl/i2001-00298-x
- [11] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, and F. Capasso, Quantum mechanical actuation of microelectromechanical system by the Casimir effect, *Science* 291, 1941 (2001). 0036-8075 10.1126/science.1057984
- [12] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, and F. Capasso, Nonlinear Micromechanical Casimir Oscillator, *Phys. Rev. Lett.* 87, 211801 (2001). 0031-9007 10.1103/PhysRevLett.87.211801
- [13] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, The Casimir force between real materials: Experiment and theory, *Rev. Mod. Phys.* 81, 1827 (2009). 0034-6861 10.1103/RevModPhys.81.1827
- [14] L. M. Woods, D. A. R. Dalvit, A. Tkatchenko, P. Rodriguez-Lopez, A. W. Rodriguez, and R. Podgornik, Materials perspective on Casimir and van der Waals interactions, *Rev. Mod. Phys.* 88, 045003 (2016). 0034-6861 10.1103/RevModPhys.88.045003
- [15] R. S. Decca, E. Fischbach, G. L. Klimchitskaya, D. E. Krause, D. López, and V. M. Mostepanenko, Improved tests of extra-dimensional physics and thermal quantum field theory from new Casimir force measurements, *Phys. Rev. D* 68, 116003 (2003). 0556-2821 10.1103/PhysRevD.68.116003
- [16] R. S. Decca, D. López, E. Fischbach, G. L. Klimchitskaya, D. E. Krause, and V. M. Mostepanenko, Precise comparison of theory and new experiment for the Casimir force leads to stronger constraints on thermal quantum effects and long-range interactions, *Ann. Phys. (N.Y.)* 318, 37 (2005). 0003-4916 10.1016/j.aop.2005.03.007
- [17] R. S. Decca, D. López, E. Fischbach, G. L. Klimchitskaya, D. E. Krause, and V. M. Mostepanenko, Tests of new physics from precise measurements of the Casimir pressure between two gold-coated plates, *Phys. Rev. D* 75, 077101 (2007). 1550-7998 10.1103/PhysRevD.75.077101
- [18] R. S. Decca, D. López, E. Fischbach, G. L. Klimchitskaya, D. E. Krause, and V. M. Mostepanenko, Novel constraints on light elementary particles and extra-dimensional physics from the Casimir effect, *Eur. Phys. J. C* 51, 963 (2007). 1434-6044 10.1140/epjc/s10052-007-0346-z
- [19] C.-C. Chang, A. A. Banishev, R. Castillo-Garza, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Gradient of the Casimir force between (Equation presented) surfaces of a sphere and a plate measured using an atomic force microscope in a frequency-shift technique, *Phys. Rev. B* 85, 165443 (2012). 1098-0121 10.1103/PhysRevB.85.165443
- [20] A. A. Banishev, C.-C. Chang, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Measurement of the gradient of the Casimir force between a nonmagnetic gold sphere and a magnetic nickel plate, *Phys. Rev. B* 85, 195422 (2012). 1098-0121 10.1103/PhysRevB.85.195422
- [21] A. A. Banishev, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Demonstration of the Casimir Force Between Ferromagnetic Surfaces of a Ni-Coated Sphere and a Ni-Coated Plate, *Phys. Rev. Lett.* 110, 137401 (2013). 0031-9007 10.1103/PhysRevLett.110.137401
- [22] A. A. Banishev, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Casimir interaction between two magnetic metals in comparison with nonmagnetic test bodies, *Phys. Rev. B* 88, 155410 (2013). 1098-0121 10.1103/PhysRevB.88.155410
- [23] G. Bimonte, D. López, and R. S. Decca, Isoelectronic determination of the thermal Casimir force, *Phys. Rev. B* 93, 184434 (2016). 2469-9950 10.1103/PhysRevB.93.184434
- [24] F. Chen, U. Mohideen, G. L. Klimchitskaya, and V. M. Mostepanenko, Investigation of the Casimir force between metal and semiconductor test bodies, *Phys. Rev. A* 72, 020101(R) (2005). 1050-2947 10.1103/PhysRevA.72.020101
- [25] F. Chen, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Demonstration of the Difference in the Casimir Force for Samples with Different Charge-Carrier Densities, *Phys. Rev. Lett.* 97, 170402 (2006). 0031-9007 10.1103/PhysRevLett.97.170402
- [26] F. Chen, U. Mohideen, G. L. Klimchitskaya, and V. M. Mostepanenko, Experimental test for the conductivity properties from the Casimir force between metal and semiconductor, *Phys. Rev. A* 74, 022103 (2006). 1050-2947 10.1103/PhysRevA.74.022103
- [27] F. Chen, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Demonstration of optically modulated dispersion forces, *Opt. Express* 15, 4823 (2007). 1094-4087 10.1364/OE.15.004823
- [28] F. Chen, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Control of the Casimir force by the modification of dielectric properties with light, *Phys. Rev. B* 76, 035338 (2007). 1098-0121 10.1103/PhysRevB.76.035338
- [29] G. Torricelli, P. J. van Zwol, O. Shpak, C. Binns, G. Palasantzas, B. J. Kooi, V. B. Svetovoy, and M. Wuttig, Switching Casimir force with phase-change materials, *Phys. Rev. A* 82, 010101(R) (2010). 1050-2947 10.1103/PhysRevA.82.010101
- [30] S. de Man, K. Heeck, R. J. Wijngaarden, and D. Iannuzzi, Halving the Casimir Force with Conductive Oxides, *Phys. Rev. Lett.* 103, 040402 (2009). 0031-9007 10.1103/PhysRevLett.103.040402

- [31] S. de Man, K. Heeck, and D. Iannuzzi, Halving the Casimir force with conductive oxides: Experimental details, *Phys. Rev. A* 82, 062512 (2010). 1050-2947 10.1103/PhysRevA.82.062512
- [32] C.-C. Chang, A. A. Banishev, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Reduction of the Casimir Force from Indium Tin Oxide Film by UV Treatment, *Phys. Rev. Lett.* 107, 090403 (2011). 0031-9007 10.1103/PhysRevLett.107.090403
- [33] A. A. Banishev, C.-C. Chang, R. Castillo-Garza, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Modifying the Casimir force between indium tin oxide plate and (Equation presented) sphere, *Phys. Rev. B* 85, 045436 (2012). 1098-0121 10.1103/PhysRevB.85.045436
- [34] M. Sedighi, V. B. Svetovoy, and G. Palasantzas, Casimir force measurements from carbide surfaces, *Phys. Rev. B* 93, 085434 (2016). 2469-9950 10.1103/PhysRevB.93.085434
- [35] H. B. Chan, Y. Bao, J. Zou, R. A. Cirelli, F. Klemens, W. M. Mansfield, and C. S. Pai, Measurement of the Casimir Force Between a Gold Sphere and a Silicon Surface with Nanoscale Trench Arrays, *Phys. Rev. Lett.* 101, 030401 (2008). 0031-9007 10.1103/PhysRevLett.101.030401
- [36] Y. Bao, R. Guérout, J. Lussange, A. Lambrecht, R. A. Cirelli, F. Klemens, W. M. Mansfield, C. S. Pai, and H. B. Chan, Casimir Force on a Surface with Shallow Nanoscale Corrugations: Geometry and Finite Conductivity Effects, *Phys. Rev. Lett.* 105, 250402 (2010). 0031-9007 10.1103/PhysRevLett.105.250402
- [37] H.-C. Chiu, G. L. Klimchitskaya, V. N. Marachevsky, V. M. Mostepanenko, and U. Mohideen, Demonstration of the asymmetric lateral Casimir force between corrugated surfaces in nonadditive regime, *Phys. Rev. B* 80, 121402(R) (2009). 1098-0121 10.1103/PhysRevB.80.121402
- [38] H.-C. Chiu, G. L. Klimchitskaya, V. N. Marachevsky, V. M. Mostepanenko, and U. Mohideen, Lateral Casimir force between sinusoidally corrugated surfaces: Asymmetric profiles, deviations from the proximity force approximation, and comparison with exact theory, *Phys. Rev. B* 81, 115417 (2010). 1098-0121 10.1103/PhysRevB.81.115417
- [39] F. Intravaia, S. Koev, I. W. Jung, A. A. Talin, P. S. Davids, R. S. Decca, V. A. Aksyuk, D. A. R. Dalvit, and D. López, Strong Casimir force reduction through metallic surface nanostructuring, *Nat. Commun.* 4, 2515 (2013). 2041-1723 10.1038/ncomms3515
- [40] J. Barcenas, L. Reyes, and R. Esquivel-Sirvent, Scaling of micro- and nanodevices actuated by the Casimir force, *Appl. Phys. Lett.* 87, 263106 (2005). 0003-6951 10.1063/1.2152835
- [41] R. Esquivel-Sirvent and R. Pérez-Pascual, Geometry and charge carrier induced stability in Casimir actuated nanodevices, *Eur. Phys. J. B* 86, 467 (2013). 1434-6028 10.1140/epjb/e2013-40779-5
- [42] W. Broer, G. Palasantzas, J. Knoester, and V. B. Svetovoy, Significance of the Casimir force and surface roughness for actuation dynamics of MEMS, *Phys. Rev. B* 87, 125413 (2013). 1098-0121 10.1103/PhysRevB.87.125413
- [43] M. Sedighi, W. Broer, G. Palasantzas, and B. J. Kooi, Sensitivity of micromechanical actuation on amorphous to crystalline phase transformations under the influence of Casimir forces, *Phys. Rev. B* 88, 165423 (2013). 1098-0121 10.1103/PhysRevB.88.165423
- [44] W. Broer, H. Waalkens, V. B. Svetovoy, J. Knoester, and G. Palasantzas, Nonlinear Actuation Dynamics of Driven Casimir Oscillators with Rough Surfaces, *Phys. Rev. Appl.* 4, 054016 (2015). 2331-7019 10.1103/PhysRevApplied.4.054016
- [45] J. Zou, Z. Marcet, A. W. Rodriguez, M. T. H. Reid, A. P. McCauley, I. I. Kravchenko, T. Lu, Y. Bao, S. G. Johnson, and H. B. Chan, Casimir forces on a silicon micromechanical chip, *Nat. Commun.* 4, 1845 (2013). 2041-1723 10.1038/ncomms2842
- [46] L. Tang, M. Wang, C. Y. Ng, M. Nolicic, C. T. Chan, A. W. Rodriguez, and H. B. Chan, Measurement of non-monotonic Casimir forces between silicon nanostructures, *Nat. Photonics* 11, 97 (2017). 1749-4885 10.1038/nphoton.2016.254
- [47] N. Inui, Optical switching of a graphene mechanical switch using the Casimir effect, *J. Appl. Phys.* 122, 104501 (2017). 0021-8979 10.1063/1.4993672
- [48] X.-F. Liu, Y. Li, and H. Jing, Casimir switch: Steering optical transparency with vacuum forces, *Sci. Rep.* 6, 27102 (2016). 2045-2322 10.1038/srep27102
- [49] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, Casimir and van der Waals force between two plates or a sphere (lens) above a plate made of real metals, *Phys. Rev. A* 61, 062107 (2000). 1050-2947 10.1103/PhysRevA.61.062107
- [50] V. M. Petrov, M. P. Petrov, V. V. Bryksin, J. Petter, and T. Tschudi, Optical detection of the Casimir force between macroscopic objects, *Opt. Lett.* 32, 3167 (2006). 0146-9592 10.1364/OL.31.003167
- [51] V. M. Petrov, M. P. Petrov, V. V. Bryksin, J. Petter, and T. Tschudi, Casimir force measurement using dynamic holography, *JETP* 104, 696 (2007) [*Zh. Eksp. Teor. Fiz.* 131, 798 (2007)]. 1063-7761 10.1134/S1063776107050032
- [52] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, *Cavity Optomechanics* (Springer, Berlin, 2014).
- [53] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, *Cavity optomechanics*, *Rev. Mod. Phys.* 86, 1391 (2014). 0034-6861 10.1103/RevModPhys.86.1391

- [54] M. Boström, C. Persson, and Bo E. Sernelius, Casimir force between atomically thin gold films, *Eur. Phys. J. B* 86, 43 (2013). 1434-6028 10.1140/epjb/e2012-31051-9
- [55] D. S. Ghosh, *Ultrathin Metal Transparent Electrodes for the Optoelectronics Industry* (Springer, Cham, 2013).
- [56] V. Petrov, J. Hahn, J. Petter, M. Petrov, and T. Tschudi, Precise subnanometer control of the position of a macro object by light pressure, *Opt. Lett.* 30, 3138 (2005). 0146-9592 10.1364/OL.30.003138
- [57] O. Suchoi and E. Buks, Sensing dispersive and dissipative forces by an optomechanical cavity, *Europhys. Lett.* 115, 14001 (2016). 0295-5075 10.1209/0295-5075/115/14001
- [58] M. S. Tomaš, Casimir force in absorbing multilayers, *Phys. Rev. A* 66, 052103 (2002). 1050-2947 10.1103/PhysRevA.66.052103
- [59] C. Raabe, L. Knöll, and D.-G. Welsch, Three-dimensional Casimir force between absorbing multilayer dielectrics, *Phys. Rev. A* 68, 033810 (2003). 1050-2947 10.1103/PhysRevA.68.033810
- [60] G. L. Klimchitskaya and V. M. Mostepanenko, Casimir and van der Waals energy of anisotropic atomically thin metallic films, *Phys. Rev. B* 92, 205410 (2015). 1098-0121 10.1103/PhysRevB.92.205410
- [61] V. M. Mostepanenko, Special features of the thermal Casimir effect across a uniaxial anisotropic film, *Phys. Rev. A* 92, 012511 (2015). 1050-2947 10.1103/PhysRevA.92.012511
- [62] L. Bergström, Hamaker constants of inorganic materials, *Adv. Colloid Interface Sci.* 70, 125 (1997). 0001-8686 10.1016/S0001-8686(97)00003-1
- [63] *Handbook of Optical Constants of Solids*, edited by E. D. Palik (Academic, New York, 1985).
- [64] C. Kittel, *Introduction to Solid State Physics* (Wiley, New York, 1996).
- [65] L. D. Landau, E. M. Lifshitz, and L. P. Pitaevskii, *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1984).
- [66] D. J. Nash and J. R. Sambles, Surface plasmon study of the optical dielectric function of silver, *J. Mod. Opt.* 43, 81 (1996). 0950-0340 10.1080/09500349608232725
- [67] I. R. Hooper and J. R. Sambles, Some considerations on the transmissivity of thin metal films, *Opt. Express* 16, 17258 (2008). 1094-4087 10.1364/OE.16.017258
- [68] T. A. Kudykina, Boundary conditions in case of electromagnetic wave absorption, *Phys. Status Solidi (b)* 160, 365 (1990). 0370-1972 10.1002/pssb.2221600136
- [69] T. A. Kudykina, Dispersion and propagation of light in crystals in the exciton absorption region, *Phys. Status Solidi (b)* 165, 591 (1991). 0370-1972 10.1002/pssb.2221650230
- [70] S. A. Kovalenko, Optical properties of thin metal films, *Semicond. Phys. Quantum Electron. Optoelectron.* 2, 13 (1999).
- [71] M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, Cambridge, 1999).
- [72] J. Xu, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Reducing detrimental electrostatic effects in Casimir-force measurements and Casimir-force-based microdevices, *Phys. Rev. A* 97, 032501 (2018). 2469-9926 10.1103/PhysRevA.97.032501
- [73] C. Metzger, M. Ludwig, C. Neuenhahn, A. Ortlieb, I. Favero, K. Karrai, and F. Marquardt, Self-Induced Oscillations in an Optomechanical System Driven by Bolometric Backreaction, *Phys. Rev. Lett.* 101, 133903 (2008). 0031-9007 10.1103/PhysRevLett.101.133903