Metamaterial ‘Gecko Toe’: Optically-Controlled Adhesion to Any Surface

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Abstract: A new optical near-field force between plasmonic metamaterials and dielectric/metallic surfaces is identified. It can exceed Casimir, radiation and gravitational forces to provide an optically-controlled adhesion mechanism mimicking the gecko toe.
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Electromagnetic forces are of fundamental importance to an enormous variety of mesoscopic systems, both man-made (e.g. optical tweezers and optomechanical systems [1, 2]) and biological (e.g. gecko toes, which stick to smooth surfaces via van der Waals forces [3]).

Here we report that in addition to the conventional, well-understood force of radiation pressure, a much stronger optically-driven force can be generated when a plasmonic metamaterial is located in the vicinity of a dielectric or metal surface. This near-field force has a resonant nature linked to the excitation of the metamaterial’s plasmonic mode and acts to close the gap between the metamaterial and the surface (Fig. 1). This ‘optical adhesion’ force exists alongside interfacial Casimir forces and, at intensities of just a few tens of nW/μm^2, can overcome both radiation pressure and, like the gecko toe, gravity.

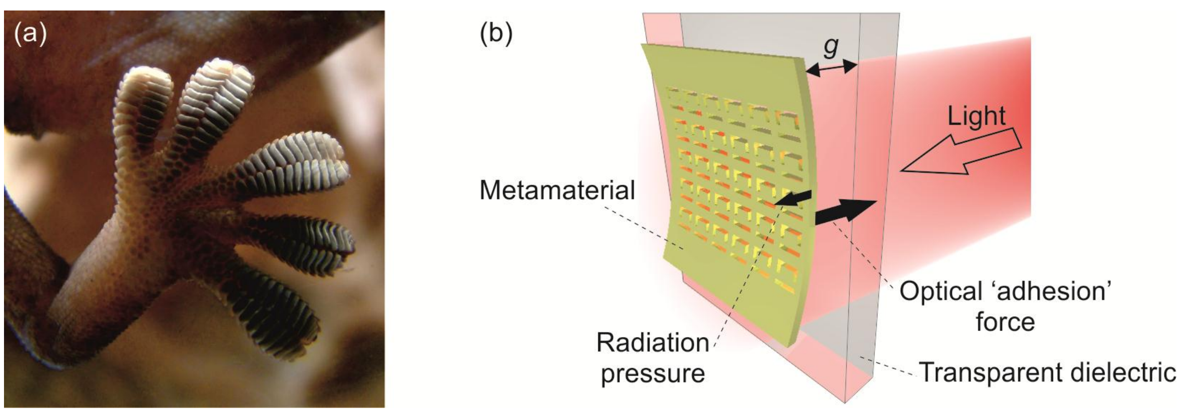

Fig. 1: (a) Gecko toes sticking to a smooth glass surface [4]; (b) Artistic impression of the nanophotonic equivalent – a planar metamaterial attracted to a dielectric surface by a beam of light.

Forces acting on a variety of metamaterial structures are evaluated using both the Maxwell stress tensor integral formalism and the energy gradient approach, which concur in predicting the magnitude and the resonant frequency dependence of the force on the wavelength of external excitation as well as dependences on the separation between metamaterial and nearby surface and on the electromagnetic properties of the surface.

Radiation pressure, arising through transfer of momentum between photons and any surface on which they impinge, can exert a maximum force (on a perfectly reflecting surface) of $2P/c$ (where P is the power of incident light and c is the speed of light in vacuum). In contrast, the near-field optical adhesion force between a metamaterial film and nearby dielectric or metal surface can be many times larger. Indeed, for a 50 nm thick gold metamaterial at a distance g = 20 nm from an unstructured gold surface it is found to exceed $50P/c$ at the metamaterial absorption resonance (Fig. 2). At this level, an illumination intensity of 60 nW/μm^2 would be sufficient to generate a force greater than that of gravity on the metamaterial film.

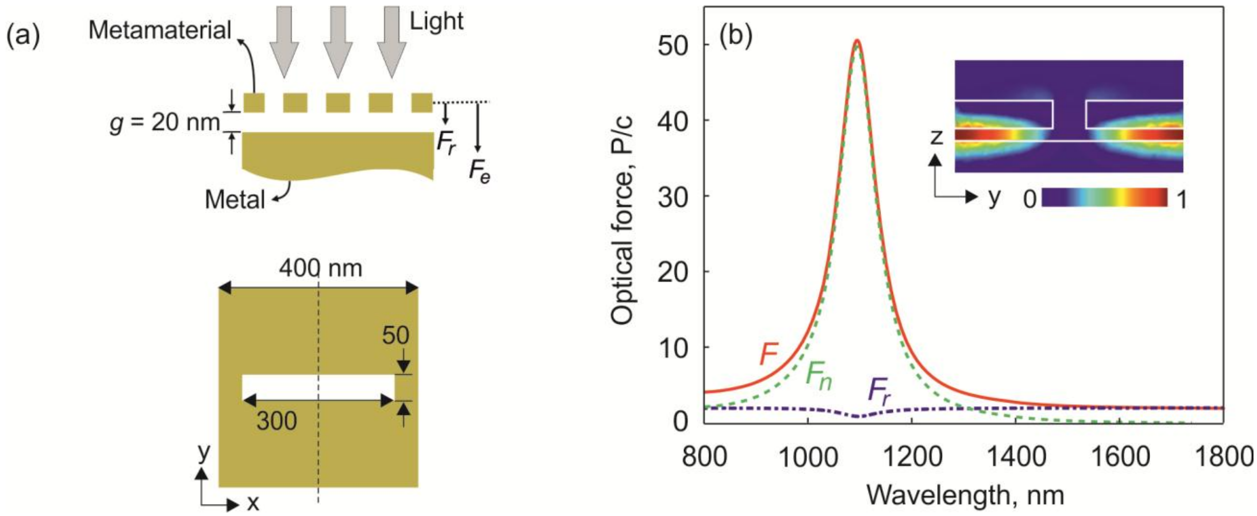

Fig. 2: Optical force between a plasmonic metamaterial and a metallic surface: (a) Schematic illustration of sample geometry and detail of metamaterial unit cell dimensions; (b) Near-field F_n, radiation pressure F_r and total optical force F acting on the metamaterial. The inset shows a map of the normalized magnetic field intensity distribution at the 1095 nm resonance wavelength for a cross-section in the y-z plane along the dashed line in (a).

At shorter distances other micro-/nanoscale forces, in particular the Casimir force, also become important. However as the Casimir force realistically scales with g^{-3} [5] while the optical near-field force is proportional to $Ie^{-g/a}$ (where I is incident intensity and a is the characteristic dimension of the nano-pattern), there will, above a certain threshold intensity, be a range of distances g where the near-field force is dominant, and this range will broaden with increasing intensity. Indeed, as a consequence the near-field force is likely to prevail where conditions such as surface roughness limit the proximity of two objects.

The near-field force holds considerable advantages for nanoscale manipulation in that it depends on both light intensity and wavelength - offering dynamic controllability and spectral selectivity. It may serve applications in optical trapping/tweezing and in the control of light with light via optically reconfigurable metamaterials.

References

[1] K. Dholakia, and T. Čižmár, "Shaping the future of manipulation," Nat. Photon. **5,** 335-342 (2011).

[2] M. Li, W. H. P. Pernice, C. Xiong, T. Baehr-Jones, M. Hochberg, and H. X. Tang, "Harnessing optical forces in integrated photonic circuits," Nature **456,** 480-485 (2008).

[3] K. Autumn, M. Sitti, Y. A. Liang, A. M. Peattie, W. R. Hansen, S. Sponberg, T. W. Kenny, R. Fearing, J. N. Israelachvili, and R. J. Full, "Evidence for van der Waals adhesion in gecko setae," Proc. Natl. Acad. Sci. USA **99,** 12252-12256 (2002).

[4] B. C. Tørrissen (Creative Commons BY-SA licence).

[5] A. W. Rodriguez, F. Capasso, and S. G. Johnson, "The Casimir effect in microstructured geometries," Nat. Photon. **5,** 211-221 (2011).