Probing light fields with nano-mechanical oscillators

Because of their ultra-low mass, nanometre-scale objects can be used to measure applied forces with exceptional sensitivity, provided one can detect their vibrations. Here, a nanowire made of Silicon Carbide has been used to map the force field exerted by a focused laser beam. It is well known that the radiation pressure can have significant effects at the macroscopic and astronomical scales. What is radically new with nanowires is that we can study the mechanical action of light at a scale smaller than the optical wavelength. In addition, we can investigate the back action of the light on the nanowire's vibrational dynamics.

In collaboration with colleagues at the Institut Lumière Matière (Lyon) we have developed an experiment to probe the vibrations of nanoscale mechanical oscillators by an optical technique. Specifically, our nano-mechanical oscillators are crystalline Silicon Carbide nanowires having ultralow masses, of one-tenth of a picogram (10^{-16} kg). These oscillators are sensitive to forces in the attonewton range (10^{-18} N). They are one million times more sensitive than the (already very sensitive) probes used in the Atomic Force Microscopes that have been revolutionizing the nanosciences in recent years. We have used this extreme sensitivity to measure and map the mechanical action of light.

A 30 µm long, 150 nm diameter nanowire (Fig. 1a) was immersed in a laser beam that was tightly focused, down to a 500 nm spot size (Fig. 1b). First, by measuring the fluctuations of the light scattered by the nanowire, we characterized the nanowire's vibrations, whose fundamental eigenmodes have frequencies in the 10^2-10^3 kHz range. We were able to measure the thermal vibrational noise of the nanoresonator, (its "Brownian motion") over a very large dynamic range. This random motion determines the intrinsic force sensitivity of the nanowire, which amounts here to a few attonewtons at the temperature of the experiment, 300 K.

By moving the nanowire within the optical spot using a very precise piezo-electric positioning device, we then measured, in each point in space, the force exerted on the wire by the light field. Because the nanowire has such a tiny diameter, we could map the light-matter interaction with sub-wavelength spatial resolution (Fig. 1c). This represents a first step towards the investigation of vectorial force fields at the nanoscale, with unequalled sensitivity.

We also investigated how the presence of the optical force field can modify the nanowire's dynamics. This perturbation presents a fundamental character since it represents the return action or "back-action" of the optical measurement process, to which all measurement systems are intrinsically submitted.

In particular, we have investigated how the detailed shape of the vectorial force field (its "topology") was impacting the nanowire's dynamics. We have discovered a novel dynamical instability of the nanowire, leading to very large self-sustained oscillations, that appears in regions of strong vorticity of the light field. The existence of these regions is a consequence of the non-conservative character of the light-matter interaction. The regions of large shear can be directly visualized in the measured force-field's cartography (Fig. 1c), on each side of the optical axis.

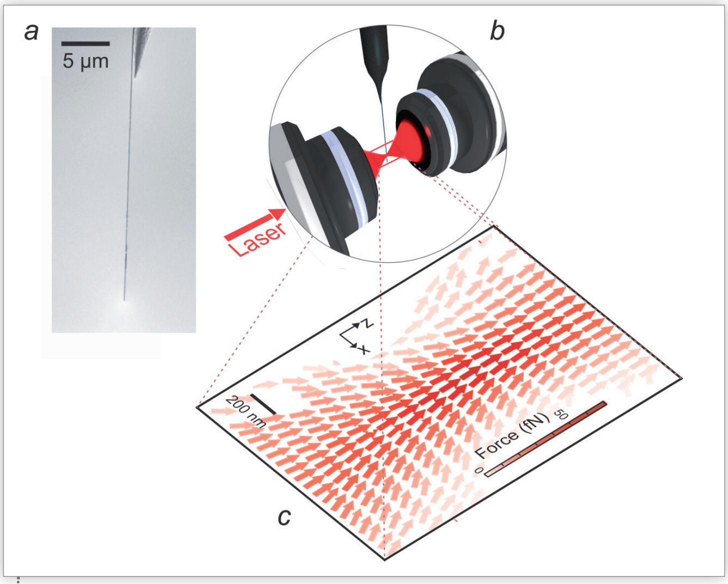

Fig. 1: ***(a)*** *Scanning Electron Microscope image of a 150 nm diameter Silicon Carbide nanowire, suspended at its top on a tungsten tip.*

(b) *The nanowire is piezo-positioned in a laser beam strongly focused by high numerical aperture microscope objectives. The nanowire's vibrations modulate the transmitted light beam intensity, which provides a means to characterize the nanowire's vibrations and measure its thermal noise.*

(c) *Due to a non-perfect cylindrical symmetry, each vibrational mode of the wire has two perpendicular components with slightly different frequencies. By amplitude-modulating the laser beam in resonance with these frequencies, the z and x components of the force exerted by the laser on the wire can be determined and mapped with large signal to noise (to give the field of red arrows). At high laser power, a dynamical instability is observed in regions of large shear in the vector flow, the irregularities seen here on each side of the optical axis.*

Often in physics, the dimensionality of the problem strongly affects the phenomenology observed. This is the case in this experiment, since the abovementioned dynamical instability cannot occur in the "mono-dimensional" optomechanical systems studied previously (resonators forming one end of a Fabry-Perot cavity) where the forces exerted by optical fields are conservative.

The optomechanical investigation developed in this work represents a new tool for investigating confined force fields. More generally, performing vectorial force field cartography provides a new analytical tool for investigating the light-matter interaction.

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FURTHER READING

"Nano-optomechanics and topological backaction in a non-conservative radiation force field"
A. Gloppe, P. Verlot, E. Dupont-Ferrier, A. Siria, P. Poncharal, G. Bachelier, P. Vincent, O. Arcizet
Nature Nanotechnology 9, 920 (2014).