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Device physics

Microlever chilled out

Peter W. Milonni and Boris M. Chernobrod

New work shows how light might be used to cool a micrometre-size cantilevered mirror to the low temperatures required in physics experiments and applications.

Microfabricated cantilevers have permitted by far the most sensitive studies of small forces at tiny length scales. They are the basis of, among other things, the atomic force microscope and the magnetic-resonance force microscope. Microlevers are increasingly of interest as tools for the study of materials and the development of quantum microscopes for such fundamental investigations as detection of the presence of a single unpaired electron spin¹. To reduce thermal fluctuations — and therefore increase the sensitivity of these techniques — it is generally desirable to work at low temperatures; experiments in single-spin detection, for example, are typically performed at 1.6 K. Other possible applications, such as the detection of gravitational waves or the study of the quantum superposition of states of photons or macroscopic objects, also require very low temperatures. Whereas the laser cooling of atomic gases is now commonplace, progress in the laser cooling of macroscopic objects has been less dramatic. On page 1002 of this issue, Hhberger Metzger and Karrai² report a promising step in this direction.

Their work builds on earlier studies of radiation forces acting on macroscopic objects, in particular a mechanical effect of radiation³ that is used to cool one of the mirrors of an optical resonator, using feedback control⁴. With a resonator consisting of two parallel and highly reflecting mirrors, the phase of the laser light that is reflected from the resonator varies markedly with changes in the separation of the mirrors. Measurement of the phase variation in this laser light allows detection of the thermal (brownian) motion of a mirror if it is sufficiently lightweight. It can also provide the signal for a feedback loop that controls the motion of the mirror, by adjusting the force, resulting from radiation pressure, that is exerted on it by a second laser beam: if the force is adjusted so that it opposes the motion of the mirror, this results in a reduction (cooling) of the mirror's brownian motion.

But the microlever cooling technique reported by Hhberger Metzger and Karrai²

does not use a feedback loop or radiation pressure from a second laser. Instead, it relies on the force on a resonator mirror that is generated by the light inside the resonator. This force could be simply radiation pressure, or a photo-thermal stress resulting from the absorption of radiation by different parts of the mirror possessing different coefficients of thermal expansion (such as the bulk of the microlever and a metal coating). In either case, the force is proportional to the intensity of light stored in the cavity between the mirrors, and is greatest when the separation of the mirrors is such that the laser wavelength matches a cavity (Fabry–Prot) resonance.

Because the mirror separation is changed by the force, it is strongly coupled to the light intensity inside the cavity. Changes in this intensity do not occur instantaneously with mirror separation. Therefore, the delay in the response of the intensity to a change in the mirror separation leads to a force that can enhance or oppose the motion of a mirror, depending on whether the optical frequency is higher or lower than that of the cavity resonance. The motion of the mirror can be modelled using Newton's second law, having a total force that includes this intensity-dependent force, as well as a fluctuating thermal force. Such a model accounts accurately for Hhberger Metzger and Karrai's results².

In their experiment, the resonator is formed, inside a vacuum, by two mirrors: one is a semi-transparent gold film across the end of an optical fibre, and the other is a gold-coated silicon microlever of dimensions $223\text{ }\mu\text{m} \times 22\text{ }\mu\text{m} \times 0.46\text{ }\mu\text{m}$ (Fig. 1). The separation of the mirrors is about $34\text{ }\mu\text{m}$. Light from a HeNe laser (with a wavelength of 633 nm) propagates from the fibre into the resonator; the light reflected from the resonator propagates back through the fibre and is analysed to deduce the thermal noise spectrum of the microlever displacement and therefore its temperature. In this way, the authors determined that the microlever temperature was reduced as the laser power increased, cooling from room temperature to a temperature of 18 K. This corresponds to a reduction of nearly a factor of 100 in

Figure 1 Cool for cavities. In the experimental set-up used by Hhberger Metzger and Karrai², laser light passing through an optical fibre is reflected by the mirrors formed by a gold film on the tip of the fibre and a gold-coated silicon microlever. Inside this resonant cavity, the light exerts pressure on the microlever, through radiation pressure or through the forces induced by absorption of the light (a photo-thermal effect, which the authors² believe dominates here). The signal transmitted back through the optical fibre is used to deduce the thermal noise spectrum and therefore the reduction in temperature resulting from the light pressure inside the cavity.

the amplitude of the brownian motion.

The key ingredient for the cooling effect is a force that is delayed with respect to a change in the mirror separation. Because of the small mirror separation and low mirror reflectivities, the radiation pressure in this experiment changes almost instantaneously with fluctuations in the microlever displacement. This cooling effect is therefore attributed by the authors² to a photo-thermal (bolometric) force. The degree of cooling will be limited by the residual heating that results from optical absorption by the lever as well as the lever's fundamental quantum fluctuations; but, theoretically at least, cooling to sub-millikelvin temperatures is feasible with this technique. ■

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