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Synthetic force fields in 2D nanomechanics based on realtime active feedback

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We first demonstrate a nanowire-based vectorial force field nanoscopy experiment capable of imaging two dimensional force fields in quasi real-time. This is achieved by optical detection of the driven motion of a vertically oriented singly clamped nanowire. The nanowire is free to oscillate in the horizontal plane with two perpendicular eigenmodes with quasi identical frequencies. When inserted in an external force field, the oscillation's properties will be dressed by the force field's local gradients. By tracking the dressed frequencies and eigenmode orientations we can reconstruct the force field gradient matrix and the force field itself.

In previous experiments based on thermal noise analysis in 2D, our group has characterized force fields around a metallic tip [2], and analyzed their impact on the nanowire probe's dynamics, including the case of a rotational force field [1,3]. Here, we developed an approach based on coherently driven trajectories, using one phase locked loop (PLL) per resonance to track both eigenmodes perturbations. With a 100 times faster measurement rate, a quasi realtime force gradient detection is now possible. The advanced approach allows for better control of the experiment and access to more evolved experiments such as the detection of magnetic forces or the investigation of the single spin-oscillator interaction.

This technique is, however, limited to cases where the nanowire eigenmodes do not rotate significantly – they may get out of phase with the PLL if they turn by 90° under the action of the external force field. One way to avoid this would be to apply an artificial force gradient on the nanowire, which could compensate the force field under investigation, so that the nanowire's mechanical properties would remain unaffected.

Here, we present a FPGA-based real time feedback technique which can be used as an artificial compensation force field. The feedback architecture is based on a readout of the nanowire motion, projected along an adjustable measurement vector, whose fluctuations are transformed into a force via an electrostatic force applied along an adjustable orientation. Depending on the relative orientations of the measurement and force feedback vectors with respect to the nanowire, this approach allows to emulate any class of uniaxial 2D force field gradient. In particular, if both vectors are non-collinear, the feedback architecture generates a rotational force field of non-conservative nature, which allows to rotate the nanowire eigenvectors. On the contrary, if both vectors are collinear and aligned with one eigenmode, it is possible to finely tune the eigenfrequency of the mode.

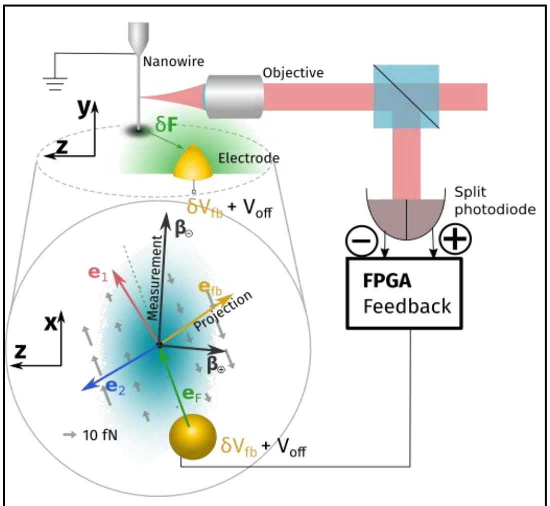

Figure 1: Illustration of the active feedback scheme in the transverse configuration (the feedback force is applied perpendicularly to the readout angle). Insert: the position noise trajectories of the nanowire is shown below the vectorial structure of the artificial force field shown in gray.

We present results for the instantaneous feedback, which for the transverse case leads to a squeezing of the noise trajectory in the displacement and velocity spaces, while generating circulation in the nanowire trajectories. We also investigate the delayed feedback case (when the feedback force is proportional to the projected speed), which allows to implement a cold damping mechanism on a single eigenmode of the nanowire in the collinear case. The later can also be used to generate exotic mechanical properties, such as transforming one nanowire eigenmode into a circular mode.

[1] Gloppe, A. *et al, Nature Nanotechnology* **9**, 920–926 (2014).
[2] de Lépinay, L. M. *et al, Nature Nanotechnology* **12**, 156–162 (2017).
[3] de Lépinay, L. M. *et al*, *Nature Comm*. **9**, 1401 (2018).
[4] Heringlake, P. et al, in preparation (2021).