Supporting Information, Cavity-assisted manipulation of freely rotating silicon nanorods in high vacuum

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The following figures S1-S3 display the simulated dynamics of a $L = 800\,\mathrm{nm}$ long and $D = 100\,\mathrm{nm}$ thick silicon rod with mass M and moment of inertia $\Theta = ML^2/12$, which rotates in the plane perpendicular to the cavity z-axis. In this case the rod can be treated as a sub-wavelength particle at position $z(t)$, and its orientation with respect to the field polarization x-axis is described by $\boldsymbol{n} = (\cos\phi(t), \sin\phi(t), 0)$. Given a constant intra-cavity field amplitude E_0, the rod's motion is governed by the following classical equations of motion:

$$\ddot{z}(t) = -\frac{E_0^2 k}{4M}\left[\alpha_\perp + \left(\alpha_\parallel - \alpha_\perp\right)\cos^2\phi\right]\sin\left(2kz\right) e^{-2\frac{(v_x t)^2}{\omega_0^2}}$$
$$\ddot{\phi}(t) = -\frac{E_0^2}{4\Theta}\left(\alpha_\parallel - \alpha_\perp\right)\sin\left(2\phi\right)\cos^2\left(kz\right) e^{-2\frac{(v_x t)^2}{\omega_0^2}}$$

with ω_0 the cavity waist, v_x the vertical velocity of the rod, and $\alpha_{\parallel,\perp}$ the polarizability components, as given in the main text. Particle trajectories that do not pass through the cavity center, but slightly off-axis, can be accounted for by decreasing the field amplitude E_0 below the cavity value $\sqrt{4I_C/c\varepsilon_0}$. The corresponding scattering intensity is obtained by evaluating the expression given in the Methods section along the simulated trajectory. Since the scattering signal is here proportional to $S_\mathrm{N} \propto \cos^2\left(kz\right)\exp\left(-2v_x^2t^2/\omega_0^2\right)$, the center-of-mass trajectory of a freely rotating rod can be reconstructed from the measured scattering signal by averaging over the fast rotation period.

We ensure that we capture the full transit through the cavity mode by carrying out each simulation over the time interval between $\pm 10\omega_0/v_x$. In order to compare this to the measured data, the scattering signal must be normalized, and the time offset of the simulation must be adjusted, accordingly.

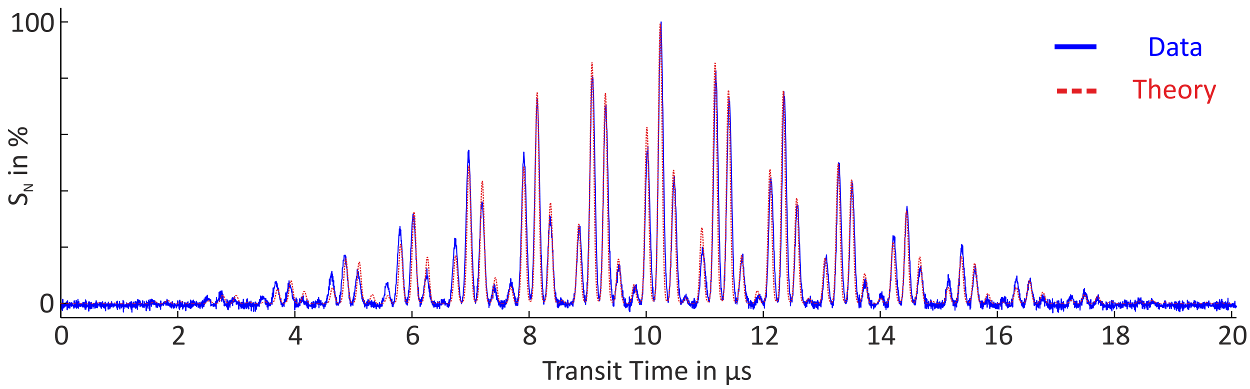

Figure S1: **Normalized scattering signal of a freely rotating nanorod.** Simulated signal as a function of time (red dashed line) in comparison to experimental data (blue solid line). The following parameters and initial values were assumed: $E_0 = 4.15 \times 10^6\,\mathrm{V/m}$, $v_x = 11.5\,\mathrm{m/s}$, $z(0) = -89.85/k$, $\dot{z}(0) = 0.74\,\mathrm{m/s}$, $\phi(0) = 0.1\,\mathrm{rad}$, $\dot{\phi}(0)/2\pi = 2.14\,\mathrm{MHz}$.

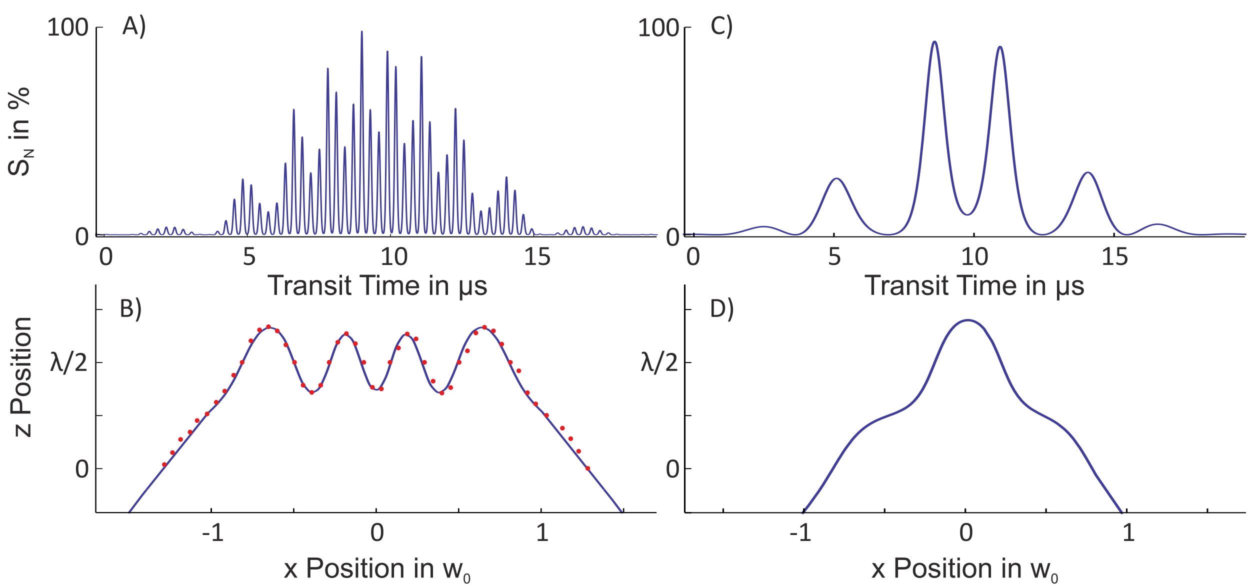

Figure S2: **Simulation of a 1d-channelled nanorod.** (A) Normalized scattering signal of a 1d-channelled particle. (B) Simulated center-of-mass trajectory (blue solid line), compared to the trajectory reconstructed from the experimental data (red dots). The following parameters and initial values were assumed: $E_0 = 8.2 \times 10^6\,\mathrm{V/m}$, $v_x = 11.3\,\mathrm{m/s}$, $z(0) = -91/k$, $\dot{z}(0) = 0.28\,\mathrm{m/s}$, $\phi(0) = -0.4\,\mathrm{rad}$, $\dot{\phi}(0)/2\pi = 1.685\,\mathrm{MHz}$. The scattering behaviour (C) and trajectory (D) of a sub-wavelength silicon nanosphere of the same mass is simulated for identical parameters. It illustrates that spherical particles are subjected to weaker optical forces compared to rods.

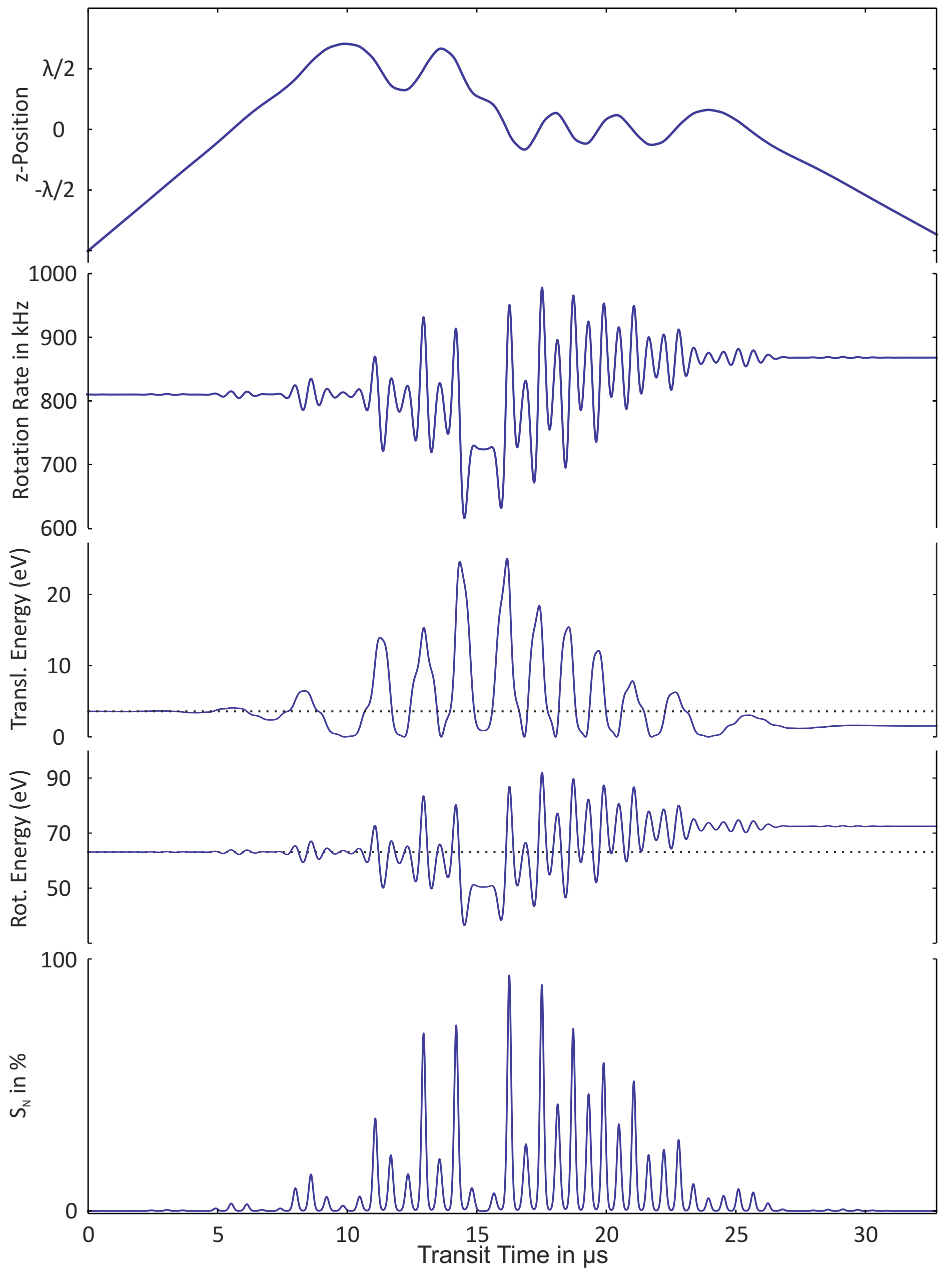

Figure S3: **Simulation of translational and rotational manipulation of a rod.** This simulation qualitatively resembles the case displayed in Figure 4 of the main text. The motional and rotational degrees of freedom couple via the optical potential, most dominantly after approximately $15\,\mu$s. At this point, the channelled rod escapes the trapping potential of an anti-node and falls into the adjacent one, while the rotation rate temporarily slows down. The following parameters and initial values were assumed: $E_0 = 8.0 \times 10^6\,\mathrm{V/m}$, $v_x = 7.94\,\mathrm{m/s}$, $z(0) = -99/k$, $\dot{z}(0) = 0.28\,\mathrm{m/s}$, $\phi(0) = -0.10098\,\mathrm{rad}$, $\dot{\phi}(0)/2\pi = 810\,\mathrm{kHz}$. After transit, we find a $7\,\%$ higher rotation rate, whereas the on-axis velocity is reduced by $34\,\%$.