Nanophotonic trapping for precise manipulation of biomolecular arrays

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Supplementary Section 1. Device fabrication

The device fabrication process was based on and slightly modified from a previous method\(^1\). In brief, the process began with patterning the silicon waveguides on a SOI wafer using electron-beam lithography and plasma etching, followed by sputtering a thin layer (~ 50 nm) of chromium (Cr) over the entire wafer. Then, using optical lithography and wet etching with Cr etchant, the Cr from the entire device except the region which would ultimately become the fluidic pool was removed. The process continued by depositing a 1 µm plasma-enhanced chemical vapor deposition (PECVD) oxide, followed with two subsequent steps of lithography, metal evaporation, and lift-off to define the metal microheaters (Ni, 2.5 µm wide and 200 nm thick) and the contact electrodes (Al). The heat localization of the microheaters and their large distance (150 µm) from the fluidic pool ensured almost no temperature increase in the fluidic region (< 0.1°C) due to the microheaters. Then, the entire wafer was covered by another 1.5 µm of oxide. In the next step, optical lithography and plasma etching removed the oxide cladding from the fluidic pool and the etching stopped at the Cr interface. Then, using a Cr wet etchant, the Cr layer was removed from the fluidic region. A subsequent step of optical lithography and plasma etching removed the oxide from a portion of the Al contact electrodes and exposed them to the off-chip metal probes. Finally, the chip was integrated with a fluidic channel for fluid delivery.
Figure S1. Stiffness of an nSWAT: measurements and calculations.

(a) Experimental measurement of stiffness – method 1. A 490 nm diameter polystyrene bead was held in a trap on an nSWAT and its position along the waveguide \((x)\) was recorded as a function of time. The bead position distribution (red bars) was fit to a Gaussian (blue curve). The stiffness was calculated from the variance of the bead position using the equipartition theorem: the position variance \(\sigma^2 = 504 \text{ nm}^2\) corresponds to a stiffness \(k_x = \frac{k_B T}{\sigma^2} = 0.0082\) pN/nm. The laser power at the input fiber before coupling to the chip was 134 mW. We estimate that the laser power in the waveguide at the trapping region was 20-30 mW for this measurement.

(b) Experimental measurement of stiffness – method 2. For the same set of data, the stiffness was also determined from the power spectrum of the bead position. The measured power spectrum (black curve) was fit to a Lorentzian function of the form (blue dashed curve)\(^2\):

\[
P(f) = \frac{k_B T}{2 \pi^3 \gamma (f^2 + f_c^2)},
\]

where \(f\) is the frequency, \(k_B T\) is the thermal energy (4.1 pN•nm at room temperature), \(\gamma\) is the viscous drag coefficient for the bead, and \(f_c\) is the corner frequency of the Lorentzian. The fit yielded \(f_c = 105\) Hz, and \(\gamma = 1.21 \times 10^{-5}\) pN/(nm•Hz) and trap stiffness, \(k_x = 2 \pi \gamma f_c = 0.0080\) pN/nm.

(c) Trap stiffness versus laser power in the waveguide. The average stiffness measured for several 490 nm diameter beads at different estimated laser powers in the waveguide at the trapping region, determined from the variance method (red open circles) and the power spectrum method (black filled squares). Error bars represent s.e.m. Fitting these results to a line gives stiffness 0.26 pN/nm per watt for the variance method (red dashed line) and 0.24 pN/nm per watt for the power spectrum method (black dashed line). This trap stiffness is comparable to that of a conventional optical trap, which is typically \(\sim 0.2\) pN/nm per watt axially (along the direction of trapping laser propagation)\(^3\), and \(\sim 1\) pN/nm per watt laterally.
(perpendicular to the direction of trapping laser propagation)\(^4\). In order to generate multiple traps of similar stiffness, there is no need to increase the laser power for nSWAT since it naturally contains multiple traps. In contrast, for the table-top optical traps, the laser power would have to increase in proportion to the number of traps.

(d) Calculated trap stiffness versus polystyrene bead size. This calculation was performed by electromagnetic simulation of the standing-wave in the waveguide and its interaction with a bead whose surface was 10 nm above the waveguide. Using the Maxwell stress tensor, the net force and stiffness of the trap were obtained. All the analysis was performed for the transverse-magnetic (TM) mode of the waveguide. As seen from this figure, trap stiffness was optimal even for a bead size somewhat larger than the periodicity of the standing wave (430 nm).

(e) and (f) Cross sections of the waveguide showing the squared magnitude of the electric field (\(|E|^2\)) and the total energy density, respectively, for the TM mode of the waveguide.
The displacement of a polystyrene bead was monitored as the voltage applied to the microheater was increased in order to translate the standing-wave. This figure shows that the bead displacement increases linearly with the square of the voltage. This is because the phase difference of the counter-propagating waves increases linearly with the temperature of the waveguide due to the thermo-optic effect which results in a change in the refractive index of the waveguide. Since the temperature is proportional to the heater power or the square of the voltage, the resulting trap displacement is linearly proportional to the square of the voltage. This plot was used as a calibration for fine positioning of the traps in an nSWAT based on the microheater voltage.
Figure S3. Position of a trapped bead as it was transported along the waveguide in the presence of a large perturbing vibration. The trap was moved in a sawtooth fashion as the microscope was subjected to rather large (~ 300 nm) vibrations created by tapping of the experimental setup. While these vibrations were evident in the absolute bead position, these vibrations were essentially absent in the bead position relative to the substrate.

In comparison, precision measurements with a table-top optical trap must be made by taking extreme measures to minimize trap movement relative to the specimen plane due to environmental perturbations. For example, measurements need to take place in a sound-proof room with some experiments even requiring remote control from outside the room to further isolate both temperature or noise perturbations. Therefore gently touching a sample holder during a measurement, much less tapping on it, would certainly negatively impact experimental measurements. In order to demonstrate the exceptional stability of our device (as compared to table-top optical traps), we did precisely what has been considered disastrous with a conventional optical trap: we tapped on the nSWAT sample holder as the measurement was
taking place. The tapping indeed introduced rather large vibrations of the sample chamber itself (~ 300 nm) (black). However, there were essentially no vibrations of a trapped bead relative to the chamber (red). As we have discussed in the main text, this inherent stability is due to the fact that all optical elements creating the traps are on chip with a short path difference (~ 100 μm) between the counter-propagating waves. A bead in a conventional optical trap would have reacted to a similar perturbation by exhibiting vibrations relative to its chamber with amplitude on the order of ~ 300 nm.
Fig. S4. Measuring the response time of the microheater.

A square-wave voltage was applied to the microheater on the MZ switch and the power of the laser output was monitored by a high-speed photodetector. This plot shows that the rise time was \(~ 20 \, \mu s\) and the fall time was \(~ 32 \, \mu s\). This demonstrates that the microheater can operate at frequencies of \(~ 30 \, \text{kHz}\), comparable to that of our previous device\(^1\).
Figure S5. Standing wave trap periodicity.

For Figure 3, when the beads were held stationary on the upper nSWAT, we measured the position of each trapped bead on the waveguide. We found that the spacing between two adjacent beads to be 423 nm. We compared this value with that from our theoretical prediction. By simulating the electromagnetic mode of the waveguide at 1550 nm wavelength for the TM polarization, we found the effective index of this mode to be $n_{\text{eff}} \sim 1.89$, yielding a period of the standing-wave $\lambda/(2n_{\text{eff}}) = 410$ nm, in close agreement with the measured value.
**Video S1.** Controlled long range transportation by an nSWAT.

Initially, beads are trapped on the upper waveguide. At $t = 1$ s, the standing wave is moved to the right at 820 nm/s, and then at $t = 6$ s, the direction of motion is reversed. At $t = 13$ s, the laser power is switched to the lower waveguide, and a modest flow is applied to direct the beads downward. Then the back and forth motion is repeated on the lower waveguide from $t = 16-26$ s.
**Video S2.** Sorting and manipulation of individual DNA molecules.

Initially both waveguides are switched on, and there are a large number of beads trapped on the lower waveguide. At $t = 0$, the lower waveguide is switched off, and a downward flow is applied. This removes single beads on the lower waveguide while retaining tethered beads. At $t = 18$ s, the laser power is switched to the lower waveguide, and an upward flow is applied, removing single beads from the upper waveguide. Then at $t = 20$ s, both waveguides are again switched on, and the standing wave in the lower waveguide is moved to the left, extending the tethered DNA.
**Video S3.** On-chip changes of chemical environment of biomolecules with simultaneous fluorescence monitoring.

The video shows simultaneous fluorescence (upper panel) and bright field views (lower panel) of the sample plane on the nSWAT chip. There were two adjacent downward laminar flows. The left laminar flow contained a mixture of free Qdots and Qdots-labeled polystyrene beads (490 nm in diameter). Qdots were attached to the beads via 30 bp DNAs. The labeled beads were trapped by the upper nSWAT and transported to the right laminar flow (observation buffer) and then held there. Subsequently, they were released by turning off the upper nSWAT trap. During the entire experiment, the lower nSWAT was off.

The video was created by capturing alternating fluorescence and bright field frames. A shutter was used to switch between bright field and fluorescence illumination. This resulted in both bright field and fluorescence being recorded at 5 fps. The video is displayed at 10 fps.
References

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