AN ELECTROSTATIC CONTROLLED NEAR-FIELD NANO-OPTO-PROBE FOR NANO MANIPULATION

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ABSTRACT
This paper presents an electrostatic controlled near-field nano-opto-probe (NOP), which has high potential for nano-particle trapping, transport and release. Infrared light trapping is utilized to avoid possible optical damage to the biological particles. Within the scheme of nano-electro-mechanical systems (NEMS), this NOP combines the advantages of compact integration, precise nm-scale positioning and high resonant frequencies.

KEYWORDS
Optical force, electrostatic force, near-field, probe, nanomanipulation, NEMS

INTRODUCTION
A wide variety of optical traps based on optical scattering and gradient forces have been demonstrated for the trapping of dielectric particles [1-4]. The scattering force is proportional to the optical intensity and acts in the direction of incident light. The gradient force is proportional to the gradient of intensity. A single beam gradient force trap is practically one of the simplest trapping methods. It enables linear manipulation of nanometer and micrometer sized particles, by focusing a laser beam with an objective of high numerical aperture, and attracting particles towards the center of the beam [3-4].

The single-beam gradient force trap is obvious for particles. Conventional optical tweezers are limited to trapping particles when the diameter is comparable with the incident optical wavelength [5-6]. Trapping dielectric particles of sub-micrometer in diameters is extremely difficult since the gradient force for a Rayleigh particle scales down with a smaller diameter.

The near-field optical trapping devices are expected to break this limitation by providing higher trapping force for the trapping and release of nanoparticles [7-8]. However, most of the near-field traps utilize visible laser light, which may damage the living biological particles, like bacteria and viruses at high optical intensity of several microwatt [9]. Thus these traps are not suitable for biological particle manipulation. Compared with the traps with visible laser light, the traps with infrared (IR) laser light are able to capture the living particles at relatively higher power without causing significant damage [9]. It allows also higher manipulation velocities of the particles during capture. Taper fiber probe is one of the most used IR near-field traps devices. But for the transport of the trapped particles, a complex mechanical system is needed to control the movement of taper fiber probes, which occupies large space, and the positioning resolution is limited. The development of nano-electro-mechanical system (NEMS) technology [10-13] makes it possible to integrate the mechanical system onto a chip, which could be easily used in conjunction with other photonic elements.

In this paper, an on-chip electrostatic controlled near-field nano-opto-probe (NOP) is developed, which is potentially applied for manipulating nano-particles. IR laser light is used to avoid possible damage at relatively high optical power, which enables the trapping of nano-size particles. Besides, within the scheme of NEMS, this NOP has high resonant frequencies (MHz) and precise nm-scale positioning.

DESIGN AND THEORY
The schematic design of the NOP is illustrated in Fig. 1. The system consists of a fixed-free cantilever (nano-probe is formed at the tip), a rib-structure, and pads for electrical connection.

Figure 1: Schematic of the electrostatic force driven near field nano-opto-probe for nano particle manipulation.

The IR light is transmitted by an optical waveguide with its width decreases from 500 nm to 160 nm. The nano-probe is actuated in the lateral direction by the electrostatic force, and the trapped particles can be carried and transported. The gap between the probe and the dielectric pad is 2.5 μm on both sides. The dielectric pad is made of doped silicon, and connected with metal pad. The voltage signal is conducted from the rib to the probe via the silicon waveguide. Light is coupled into the NOP from
500-nm width port, and is focused at the tip of the NOP to generate the gradient optical force. Nanoparticles located near the tip of the probe are trapped due to the gradient optical force. When the optical probe is actuated by electrostatic force, the trapped particles will be transported to a new location within 5-μm distance.

![Image](image.png)

**Figure 2:** Calculated near field optical trapping force.

The gradient trapping force can be calculated with

\[ F = \frac{n^3 r^3}{2 \left( m^2 - 1 \right)} \nabla E^2, \tag{1} \]

where \( n \) is the refractive index of the medium, \( r \) is the radius of the particle, and \( E \) is the electrical field of the light at the tip of the probe. The optical trapping force increases linearly with the applied optical power. But the power obviously cannot be increased infinitely in order to avoid the heating of the particles and the surrounding medium, and any possible optical damages of the live samples. Besides, the optical trapping ability of a nano-probe with fixed shape is depending to the dimension of the targeted particles. Force in optical traps for nanometer scale particles is usually in the order of femtonewton. When the optical power in the waveguide is 50 mW, the magnitude of the optical trapping force for different particle diameters is calculated as shown in Fig. 2. For particles with diameter of 100 nm, the trapping optical force is 0.5 fN, which is sufficiently large to capture these nanoparticles.

The mechanical properties of the NOP and the possibility of utilizing electrostatic force to control the NOP are studied in Fig. 3. Fig. 3(a) presents the effective stiffness and resonant frequency of the NOP when the width and height of the cantilever are shrunk to several hundreds of nanometer scale. By increasing the beam length from 8 to 16 μm, the effective stiffness of the NOP decreases from 0.126 to 0.025 N/m, and the resonant frequency decreases from 2.7 MHz to 0.7 MHz. Optimal beam length is designed by considering both the performance of stiffness and resonant frequency. When the cantilever length is 12 μm, a stiffness of 0.04 N/m and a resonant frequency of 1.2 MHz are expected.

![Image](image.png)

**Figure 3:** (a) Effective stiffness and resonant frequency determined by dimensions. (b) Positioning of the NOP as a function of voltages.

As a typical electrostatic force actuated device, the NOP is predicted to have pull-in nonlinearity as shown in Fig. 3(b). With the initial gap between the NOP and the dielectrical pad to be 2.5 μm, the controllable actuation range is 1.2 μm in the lateral direction at both sides. The pull-in voltage can be lowered by increasing the length of the probe and decreasing the gap between the probe and the dielectric pads.

**FABRICATION AND EXPERIMENTS**

The NOP system is fabricated on silicon on isolator wafer with a top silicon layer of 220 nm. The SEM image of the NOP is shown in Fig. 4. The straight waveguide and the dielectric pads are made of silicon. The probe is made free-standing by remove the SiO2 under it by HF etching. During the HF etching, other parts on the wafer are protected by a 100-nm thick Si3N4 layer. The length of the NOP is 12 μm, which is defined by the dimension of the released window. Two silicon pads are patterned 1.6 μm away from the probe at both sides. The rib structure is used for conducting voltage from the electrical pad to the probe. The rib-cover is used to reduce the coupling loss caused by mode-mismatch when the light is guided from the rib-waveguide to the rectangular waveguide. The NOP has a width of 160 nm and a height of 220 nm at the tip of the
released waveguide.

![Figure 4: SEM image of the nano-opto-probe at the end of a nano cantilever waveguide.](image)

Figure 4: SEM image of the nano-opto-probe at the end of a nano cantilever waveguide.

To demonstrate the ability to transport the trapped nanoparticles in space, experiments are performed to actuate the probe via an electrostatic force. In the Proof-of-Concept experiments, a 1550-nm single-mode laser with a constant power is used as the light source. The light is coupled in and out of the optical waveguide via taper optical fibers, and the transmission power is detected. Initially, the NOP is aligned precisely with a taper output fiber, and the maximum transmission position is detected, which is defined as the position “zero”. For the coupling between the taper fiber and the tip waveguide, the detected transmitted optical power is sensitive to even nanometer scale misalignment. In this way, the nanometer scale movement of the probe can be detected by monitoring the varies of the transmitted optical power.

First, the position of the NOP is fixed, and the position of the taper fiber is actuated by a commercial motor in the lateral direction with a step of 50 nm. The transmission power is recorded at different auction positions of the optical fiber, from -3 to 3 µm. Thus a reference data is achieved which shows the change of the optical power as a function of the misalignment, as shown in Fig. 5. Next, the position of the taper fiber is fixed and the NOP is actuated by the electrostatic force. Referring to the data in the first step, when changing voltage to actuate the NOP by electrostatic force, 38% optical intensity degradation is observed. This value is detected before the pull-in instability occurs. This is corresponding to a stable positioning range of 1.80 µm for the NOP as indicated by the shadow area.

The curve of the NOP positioning as the function of electrostatic voltage is plotted in Fig. 6. The NOP could be precisely positioned by electrostatic force, which is monitored by the tested transmission power. The controllable actuation distance is 0.9 µm at both sides, corresponding to a transmission power degradation of 10-dB. By considering the voltage tuning step of 10 mV, the NOP positioning step is estimated to be within 2 nm.

![Figure 5: Normalized optical power vs misalignment in the lateral direction. Shadow part indicates the area where the NOP actuation is achievable.](image)

![Figure 6: Actuation distance as the function of electrostatic voltage. NOP positioning precision is estimated to be 2 nm due to 10-mV voltage tuning step.](image)

As expected, the pull-in instability phenomenon of the NOP is observed. The controllable actuation distance is 0.90-µm on both sides, when the voltage is increased from 0 to 80V. When the voltage is higher than 80 V, the NOP is pull to the electrical pad due to the pull-in instability, which corresponds to a maximum actuation distance of 2.5 µm.

CONCLUSIONS

In conclusion, an electrostatic controlled IR near-field NOP for nano-manipulation is demonstrated. The proof-of-concept experiments demonstrate a 1.80-µm controllable actuation range with a 2 nm positioning step. It can be potentially applied for manipulation of nanometer scale biological particles.

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REFERENCES


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