Optical trapping and manipulating with a transmissive and polarization-insensitive metalens: supplemental document

1. Nano-antennas Cell Parameters

Table S1. Nano-antennas Parameters

Deflection Angle (deg)	Gap[a] (nm)	$P_{angular}$[b](nm)	P_{radial} [c](nm)
73.74	50	220	417
71.81	50	220	421
68.44	50	220	430
66.93	50	220	435
64.16	50	200	444
61.64	50	195	455
58.21	50	195	471
53.13	50	185	500
48.59	50	170	533
44.43	50	170	571
33.37	85	170	727
26.74	120	170	889
20.49	175	170	1143
14.48	250	170	1600
8.63	400	170	2667

[a]The distance between the two cylinders that make up the nano-antennas.

[b]Nano-antennas' period along the angular direction of the metalens.

[c] Nano-antennas' period along the radial direction of the metalens.

2. Experimental setup for the focal spot measurement

As shown in Figure S1, the experimental focusing performance is characterized by a microscopic imaging system, including a 60× water immersion objective lens (Nikon CFI Plan Apochromat VC 60XC WI), a tube lens (LBTEK MCX10619-A), a laser source at wavelength of 532 nm and a CCD camera (Kiralux CS895CU). We generate unpolarized beam with a depolarizer (LBTEK APD10, DP). The tube lens has a focal length of 50 cm, which leads to a 150× system magnification. The actual size of focal beam intensity distribution can be calculated by dividing the recorded spot size from the CCD camera by this system magnification.

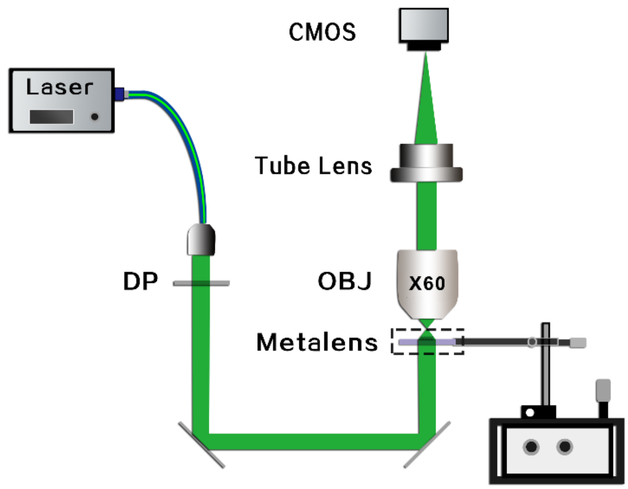

Fig. S1. Schematic diagram of the metalens focal spot measurement for unpolarized incident laser beam.

3. Mean-Square-Displacement (MSD) and Power Spectral Density (PSD) Methods for Stiffness Measurement

For the MSD method [1], the distribution probability of the trapped bead is statistically analyzed, and then the variance $\langle x^2 \rangle$ of the x-displacement of the bead from its equilibrium position can be obtained, which follows the equipartition theorem:

$$\frac{1}{2} k_B T = \frac{1}{2} \kappa_{MSD} \langle x^2 \rangle \tag{S1}$$

where k_B is the Boltzmann's constant, T is the absolute temperature and κ_{MSD} is the trapping stiffness calculated from MSD analysis.

For the PSD method [1], the one-sided power density spectrum $S_x(f)$ of the x-displacement of the bead can be described by the Lorentzian profile as:

$$S_x(f) = \frac{k_B T}{\pi^2 \beta (f^2 + f_c^2)} \tag{S2}$$

where β is the hydrodynamic drag coefficient of the bead and f_c is the corner frequency, which are associated with the trapping stiffness by

$$\kappa_{PSD} = 2\pi\beta f_c \tag{S3}$$

From Equation (S2), we can define the parameter A as:

$$A = \frac{k_B T}{\pi^2 \beta} \tag{S4}$$

In this case, the parameter A and the corner frequency f_c can both be obtained from fitting the power density spectrum $S_x(f)$. Thus, the trapping stiffness can finally be determined from Equation (S2) – (S4) as:

$$\kappa_{PSD} = \frac{2 k_B T}{\pi A} f_c \tag{S5}$$

4. Results of the Measured Stiffness

The measured trapping stiffness results for 36 individual beads with the averaged diameter of 1.76 μm at X and Y-direction using MSD and PSD method are shown in Table S2 as follow.

Table S2. Results of the measured stiffness for 36 individual beads.

MSD [pN/(μm·W)]		PSD [pN/(μm·W)]	
X	Y	X	Y
566	689	494	626
590	706	510	680
548	686	506	693
452	682	440	587
562	775	475	634
526	679	524	645
617	686	544	596
641	715	573	625
433	688	492	651
512	737	525	614
470	625	522	697
553	760	485	640
492	653	465	681
479	693	480	715
414	644	518	565
534	639	446	683
492	739	471	629
549	595	452	548
521	591	472	603
556	654	481	547
542	671	483	632
547	734	531	629
495	696	496	634
544	747	511	598
604	639	538	610
554	591	527	543
509	508	446	580
507	619	499	627
506	594	500	614
555	569	477	616
543	591	493	608
473	731	555	682
561	689	505	637
601	648	548	663
580	702	529	651
581	688	522	624

5. Simulation of the Optical Trapping Stiffness

The theoretical lateral stiffness in an optical trap varied with different bead sizes is simulated using an open-source software *optical tweezers computation toolbox* in Matlab published previously [2]. A linear polarized Gaussian beam source with wavelength of 532 nm and numerical aperture (NA) of 1.28 is used to match the parameters in our optical trapping experiments. The shape of the trapped bead is chosen as the ideal sphere, with the refractive index of the polystyrene with the value of 1.59. Bead sizes are varied from 1 μm to 4.5 μm in diameter. The refractive index of the medium is 1.33. Lateral force curves versus lateral bead displacements can be calculated for beads of different sizes and normalized by the power of the beam source, and the linear fitting of the slope for the proportional region of the lateral force curves yields the theoretical lateral stiffness, as shown in Figure S2.

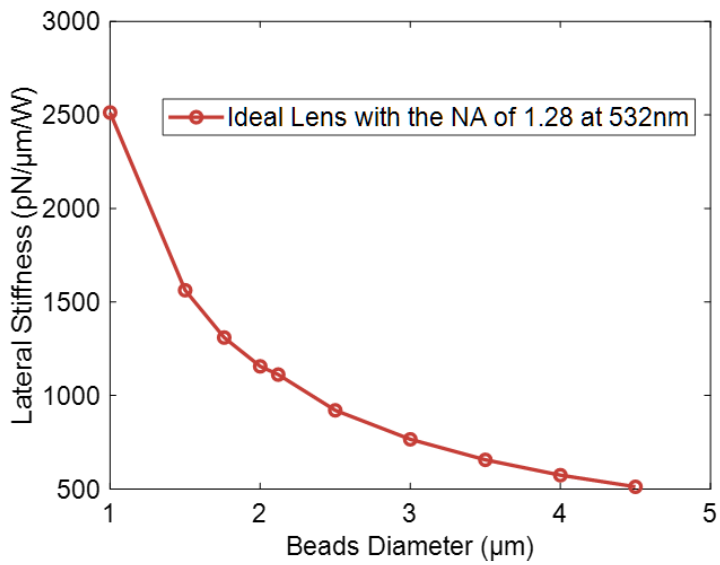

Fig. S2. The simulated optical trapping stiffness of the ideal objective or metalens with the NA of 1.28 for beads of different diameters at 532 nm.

References for Supplemental Information

1. K. C. Neuman & S. M. Block. Optical trapping. *Rev. Sci. Instrum.* **75**, 2787-2809 (2004).
2. T. A. Nieminen, et al. Optical tweezers computational toolbox. *J. Opt. A-Pure Appl. Op.* **9**, S196-S203 (2007).